THE TIDES.

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THE TIDES.

CHAPTER I.

INTRODUCTORY.

Beneficial effects of the rise and fall of tide upon navigation and commerce. Comparison of tidal and non-tidal rivers and ports. Mouths of non-tidal rivers always shallow. Rhone, Tiber, Po, Danube, Dnieper, Don, Nile, Mississippi. Advantage to the country of inland ports. Small tidal harbours on the coast. Drainage of low lands into tidal rivers. Comparison of marshes on tidal and non-tidal shores. The latter generally pestilential.

There are few daily phenomena so familiar to those who spend any time at the sea-side as the rising and falling of the tides; yet there are few so little understood. This is scarcely to be wondered at. The first answer to an inquiry upon the subject, viz. that the tides are caused by the attraction of the sun and moon, satisfies most people, not because it is a satisfactory explanation,

but because it throws a gleam of light on the subject; it gives them an idea, but one which is not particularly inviting for them to follow.

A second step in the investigation is only bewildering; it shows the utter insufficiency of this explanation to account for all the phenomena which more detailed observations disclose. It calls for some secondary cause which shall account for effects to which common sense utterly denies the right of any connexion with the attraction of the heavenly bodies. We shall endeavour in the following pages to elucidate not only the primary cause, but also some of the secondary causes which produce those phenomena which we actually see.

The subject deserves to be more popular than it is; the tides are not only eminently beautiful in their course and development, but eminently beneficial in their results. It is not too much to say, that the tides upon our coasts have had a very large share in making us as a nation what we are.

Let us examine this point a little more closely, and we do not despair of making out such a case in favour of the tides as will make our readers inclined to become further acquainted with so signal a benefactor. Taking the tide then as it is upon our shores, what does it do for us? Twice in about twenty-four hours and fifty minutes the

waters of the ocean rise and fall all around our coasts to a height of from two or three to forty or fifty feet. The waters run up into our bays and rivers, making within a few hours a change in the scene which to an inhabitant of the shores of the Mediterranean, where there is no perceptible tide, must be sufficiently striking.

Now what good does this do us? Look at our great ports: they are, London, on the Thames, fifty miles from the sea; Bristol, on the Avon, and Gloucester, on the Severn, both many miles inland; Glasgow, on the Clyde, and in the very centre of Scotland; Newcastle, ten miles up the Tyne; Hull, twenty miles up the Humber; with numerous others of secondary but still collectively of vast importance, all many miles inland, upon the banks of tidal rivers and estuaries. These ports are all more or less dependent upon the tide, Liverpool and Southampton are less so; but, as we shall have occasion to show hereafter, the probable effect upon them, if the tide were to cease, would be the gradual destruction of their harbours.

On the continent, opposite to our coasts, we find Hamburg, on the Elbe, sixty miles from the mouth; Rotterdam, on the Maas, twenty miles; Antwerp, on the Scheldt, forty-five miles inland; Rouen, on the Seine, fifty-five miles from Havre at the mouth; Nantes, thirty miles up the Loire;

Bordeaux, seventy-five miles up the Gironde; all first-class ports, sending their ships, and some of them the largest class of merchantmen, to all parts of the world. On the north coast of Spain, the rivers are small, so that their advantage is proportionally less, though we have Bilboa, seven miles up the Nervion. The Douro and the Tagus also do not, from the peculiar formation of the land near their mouths, encourage navigation farther inland than Oporto and Lisbon.

Passing along the south coast of Spain into the tideless Mediterranean, we find the great centres of trade in quite different situations. We find important ports at Malaga, Carthagena, and Barcelona, all lying on the sea-shore; we look however in vain for the river ports. The Guadaliviar, on the banks of which is situated the important town of Valencia, is utterly inapproachable, except by boats. The Ebro bringing down waters accumulated in a course of 400 miles, nearly three times the length of the Thames above London, is useless for navigation from the sea.

A little further on we come to the mouth of the Rhone, a river nearly eight times the size of the Thames, and navigable inland for 330 miles, yet at the mouth there is usually a depth of only four and a half feet[1], and even small coasting vessels

[1] Admiralty chart, compiled from French survey.

are obliged to take the canal from the sea to Arles. Marseilles and Genoa are great ports situated close to the sea.

An attempt was made in former times to make Pisa a port, but it was abandoned on account of the impossibility of navigating the Arno, and the trade was all carried to Leghorn, another sea-side artificial port.

The Tiber is useless for maritime navigation, the whole trade of the western side of the Roman States being carried on at Civita Vecchia.

The great river of northern Italy is the Po, which discharges by two mouths into the Adriatic, near Venice. There is a small rise and fall of tide here, and the Po is navigable for small vessels, but we have not been able to ascertain to what extent. There is no important trade upon it.

Three of the largest rivers in Europe discharge into the Black Sea: the Danube, the Dnieper, and the Don. Let us see the state of their entrances. The entrance to the Danube is by several small channels, that called the Soulina is the largest. There is, however, a depth of only twelve feet, which would not give a safe entrance for a vessel of 100 tons in bad weather, while a mile and a half within the mouth there is a depth of thirty-three feet. At two of the other mouths

the greatest depth is seven feet on the bars, and inside twenty to thirty feet [2].

The Dnieper below Kherson has a depth of only eight feet; and the Don, which discharges into the Sea of Azof, only five to six feet [3]: yet either of these rivers alone is as large as all the rivers of Great Britain and Ireland put together. The same may be said of the celebrated Nile, which has one mouth navigable for small vessels, the others have only about seven feet depth [4].

The Gulf of Mexico is nearly tideless. The Mississippi, which discharges into it, is about five times as large as all the rivers of France put together. At New Orleans its width is half a mile and its depth one hundred feet, yet of its many mouths only one is navigable, and that has ordinarily but thirteen feet depth of water upon it [5].

We think then we have adduced instances enough to show that as a general rule rivers do not form an available highway for maritime trade from a tideless sea, but that they are a very important feature in a country whose shores are washed by tides. One reason is obvious. If twice a day the depth of the mouth of the Rhone

[2] Admiralty chart, from Russian survey. [3] Ibid.
[4] Arrowsmith's Atlas. [5] Chart of American coast survey.

were increased from four and a half feet to fourteen and a half by a ten-feet rise of tide, the river would at once become navigable for sea-going ships. The advantage of the tide, however, is not limited by this, but its further effect being dependent on certain physical causes which we have yet to explain, it would be premature to go into it at present. We shall return to this subject in the sequel.

If it be asked where is the great advantage of such ports as London, Hamburg, Antwerp, or Bordeaux, over Marseilles, Genoa, Naples, or Odessa, we reply that, except in the very latest stages of civilization, such as that at which we are arrived, when all natural difficulties are overcome by art, when if a river does not exist, a canal or railway will be made, or even may be made to supersede one which does exist, the neighbourhood of a place of trade is a most important feature. Even in countries in an advanced state of civilization it is to the interior that we look for ignorance, superstition, and poverty. Commerce extends in all directions from the sea-ports, and brings with it employment, wealth, education, and all worldly advantages, and these diminish in proportion as the distance from trading facilities increases. Now the river ports we have named are much nearer the heart of the

country than the sea-ports, and are thus more advantageous.

Furthermore, they are generally the lower terminus of an important line of inland navigation by the river on which they are situated, and by which their benefits are still further diffused. This advantage is so great as sometimes to have induced the inhabitants to put up with the natural disadvantages of their position as regards the sea, as in the instance of New Orleans, on the Mississippi; but in general the neighbourhood of a river mouth has been avoided in choosing the site for a port: witness especially Marseilles, Leghorn, and Civita Vecchia, among many others where a river is near at hand.

A third advantage of a river is this. In the earlier stages of trade a port would often never be formed at all if much outlay were necessary. Now on the coast it is only here and there that a place is found which unites naturally the advantages of smooth water in bad weather, and facilities for loading and unloading, whereas a river is in almost every part a natural harbour. It is true that with the increase of trade, art may indefinitely increase the natural advantages of a river, but trade can at any rate begin without outlay, and can extend itself as desired. On a tideless sea-shore, except in a few exceptional localities, a

harbour must be artificially formed before trade can be accommodated.

Thus by means of tide trade can go on from a very small beginning, increasing step by step, as it has done in England, at almost all points of the coast simultaneously, gradually developing the resources of the country. Where there are no natural and well-placed harbours, trade will not be encouraged. Compare the coast of England with that of Italy, for instance; and after making due allowance for difference of character, habits, and government, a good reason for the difference of the state of trade remains in the fact that the one coast is approachable naturally at innumerable points, the other only at certain favoured localities.

These remarks apply to trading harbours only; naval stations, such as Portsmouth, Plymouth, Cherbourg, Toulon, or Sebastopol, are quite independent of tide. These are the work not of naturally developed commerce, but of political necessity, and in many respects their requirements are quite opposite to those of trading harbours.

There is yet another class of ports which are individually of less importance than the great river ports we have named, but in the aggregate of immense value to us as a nation. These are the small harbours on the sea-coast, such as Dover, Folkestone, Rye, Newhaven, Shoreham,

and many others all round Great Britain and Ireland.

These harbours are placed on the shore almost entirely between high water and low water, often but not always at the mouth of a small river. Although lying close to the sea, vessels can enter only when the tide is in. Piers have been built which are almost, if not quite dry at low water; and are thus of a construction much more economical than would have been possible if they had been built in water deep enough to float vessels at all times, where a great part of the pier would have to be built under water, a very difficult and expensive operation.

It is not too much to say, that not one in ten of these can be called a harbour of such national and general utility as to have ensured its construction if it had not been for the great facilities afforded by the tide, which enabled the local interests to undertake it. Each one manages to maintain its independent existence without state funds or state control, (with one or two rather unpopular exceptions [6],) by the little trade, both export and import, which it carries on.

But *having been constructed*, observe their public utility. But for them, in the days of difficult land carriage, when pack horses, or ponderous

[6] The question of abolishing these "passing tolls," as they are called, is now being discussed in parliament.

waggons at best, were the only means of transit, the produce of the country for miles round would have been isolated, many a now thriving little local trade would have remained undeveloped, the forest being nearly exhausted, fuel would have been, but for the sea coal trade, a most cruel burden on both rich and poor; and turning our view from the land to the sea, many a ship would have foundered for want of a refuge, many a crew would have perished, but for the timely help of that hardy race of fishermen, pilots, and coasting sailors, whose seafaring habits and employment have been called into existence and nurtured by these small tidal harbours.

Our trade is maintained perhaps more by the large ports, but our maritime character is more due to these small ports, which make the sea a home for a large class of our people. These harbours evidently could not exist without a tide. There is nothing the least analogous to them on a tideless shore.

Returning to the larger rivers, let it be observed, that although they are the highways to most of the important trading ports of the world, they do not thereby lose their character as the great drains of the country. While at high water they serve navigation, at low water they carry off effectually all the rain, which having fallen upon the land, moistened, and enriched it, having filtered

into the field drains, thence into the brooks, and thence into the main river, is carried off to sea. Now a great deal of the land which borders upon the lower parts of the rivers is below the level of high water, and would naturally never be drained at all but for the falling of the tide. The two principles of navigation and drainage are opposed to one another. The former demands high water, the latter a low level for the outfal of its channels. In the tides nature has provided a beautiful arrangement, by which half the day is given to one interest, and half to another; so that instead of one injuring the other, they mutually support and strengthen one another. These low lands, dependent upon the tide for their drainage, are some of the most valuable and productive. A large portion of the east coast of England, Lincolnshire, Cambridgeshire, and Norfolk, and a still larger proportion of Holland, are dependent partly on the falling of the tide, and partly on artificial means for their drainage.

These lands have been formed by deposits from the water at the sea level, either by the earth brought down by the rivers, and deposited when their currents are checked on falling into the sea or the expanded estuary, or by the abrasion of adjacent shores by the waves of the sea themselves. These causes exist equally in a tidal as in a tideless sea. The mouth of every river, or some sheltered

bay in the neighbourhood of every chalk or soft sandstone cliff, is the scene of the formation of a marsh. These marshes are always formed to pretty nearly the same level. On a tidal coast it is such that the high tides wash over it, each time leaving a little sediment of earthy matter. On a tideless shore the level is generally a little above that of the sea; the earthy matter being beaten up on to the shore by the waves during storms, and there left. Now observe the difference. The tideless marsh is never quite overflowed, so that the growth of all kinds of rank marshy vegetation can proceed unchecked; and this goes on accumulating and decaying, while the water, falling in the form of rain, still hangs in the ground, because the sea is too high to enable it to drain off. Such is the history of nearly every marsh formed on a tideless shore, and the effects are seen in the dreadful malaria of many parts of Italy, and other countries on the Mediterranean, on the shores of the Gulf of Mexico, and in a milder form on the coast of Jutland, where there is no tide.

On our English marshes, on the other hand, there is a frequent overflow which brings with it the salutary salt deposit, preventing a too luxuriant vegetation. The receding of the waters, on the other hand, leaves the marsh dry a sufficient time to enable it to get rid of a large proportion of its surface moisture. The result is, that our salt

marshes are in no way injurious to health, and when they are of a certain extent they can be enclosed by imbankments, which shut out the occasional overflows. They can be then more efficiently drained by means of artificial channels, carried down to low water, and closed at high water by sluice gates. They then become the great corn-growing districts.

Considerable outlay in the first instance, and the employment of some regular system of pumping the drainage water, might drain and render healthy the Mediterranean marshes; nay, in the hands of an enterprising people, it might be not only a benevolent, but a profitable work in many instances; but at any rate there would be found much fewer facilities than the reclamation of similar districts on tidal coasts presents.

Of course we only mention the rise and fall of the tide as one element in the healthy or unhealthy character of an alluvial marsh. Other causes may in certain cases reverse the effect, but on the whole we believe it will be found to be true that the tide, in the facilities it offers for the drainage of low alluvial land, is an important sanitary agent.

CHAPTER II.

PRIMARY CAUSE OF THE TIDES.

General features of the tide to be explained. Gravitation or attraction. Collection of bubbles on the surface of a liquid. Due to the same cause as the fall of a body to the earth. Level surface of water. May be disturbed by the attraction of some neighbouring large body. Force of attraction varies with mass and distance. Attraction of the moon to the earth. Different in intensity at different parts of the earth's surface. Whence if the earth be covered with water, there must necessarily be two tides for each revolution of the earth on its axis. Similar effect of the sun. Calculation of their comparative effects. Effects of all other heavenly bodies inappreciable. Combination of solar and lunar waves the cause of alternate neap and spring tides.

To enable the reader to follow us the more easily in the line of argument which we are about to lay before him, we will commence by stating generally what are the tidal phenomena we intend to explain.

The tide is the rising and falling of the sea, which takes place about twice a day, becoming however each day later by from half an hour to an

hour. The rising of the sea is called "flood tide," the falling "ebb tide." The tides do not always rise to the same height, but every fortnight, two or three days after new or full moon, they become much higher than they were in the alternate weeks. These high tides are called spring tides, the low ones neap tides. The height from low water to high water is called the *range of the tide.* The range differs very much in different parts. On our coasts it is greatest at the head of the British Channel, where spring tides sometimes rise forty-seven feet. In some other parts it is not more than three feet. The times at which high water takes place are equally various. Thus, the same day that it is high water at Dover at twelve o'clock, it is not high water at London till three, and at Hull till half-past seven.

Our task is to show, firstly, what makes the water rise and fall at all; and, secondly, what produces these variations in the range and time of the tide.

Every one has heard the old story of Sir Isaac Newton having discovered the principle of gravitation from the train of thought into which he was led by the fall of an apple from a tree.

Most people know that this principle of gravitation, evidenced in so familiar an example as the fall of an apple, is the prime mover of almost every thing (however apparently diverse) which

goes on in the physical world around us. We say most people *know*, but a much smaller number fully *understand* this point, or at least are familiar with it.

The word gravitation is generally used in connexion with Sir Isaac Newton's discovery; but "attraction" is a word of really the same meaning, though as ordinarily received of more universal application. In speaking then of attraction, it should be understood that we do not mean a principle different from gravitation, although we may apply it to examples to which the latter term would not correctly apply.

In order to present to the mind of the reader the force of attraction in the form in which it is most obviously applicable to the tides, we will take a very familiar example.

When beer or any other rather viscous liquid has been poured into a glass, the surface is covered with froth, consisting of bubbles, in which air is enclosed in a very thin film of the liquid. These bubbles quickly burst, and before long the clear surface of the liquid appears in patches. These patches gradually increase in size, and it will be observed that they have a tendency to run together, the line of bubbles which separates them parting in the middle; the bubbles on one side the parting running to the mass on one side, and those on the other to the opposite side. After a

time there remain only a comparatively few bubbles; these are to be seen round the sides of the glass, and perhaps a few in a little cluster in the middle. Now it is not that the sides or the middle of the tumbler are more favourable to the preservation of the bubbles than other parts, but that those which are strongest last longest, and their fellows being burst, they have the clear surface of the liquid to move about upon freely, and then they are attracted to the nearest point of the glass, and range themselves in a circle as close to it as they can. A few, however, near the centre are equally attracted to all parts of the glass, and so having no preference for one part more than another remain in the centre.

Now the congregation of these bubbles together and to the nearest solid substance, is due to precisely the same cause as the fall of an apple to the earth. The latter we call by a different name, but it is in fact the attraction of the earth for the apple. The attraction of so enormous a mass as the earth so overwhelms the attraction which objects on its surface mutually exert one towards another, that in peculiar circumstances only is the latter at all sensible in comparison with the former. In the case of floating bodies it is often evident, though here it acts so slowly in comparison with the rapid motion of a falling apple that we hardly recognize the analogy.

There is then an universal principle that all bodies exert an attractive force upon all other bodies. It may be too feeble to overcome resistance to movement, it may be so small that we do not observe it in comparison with the attraction of one great body, which, as we see it every day, we do not think of by this scientific name attraction; but it exists in all bodies as a property of matter, and will become manifest whenever circumstances allow it.

Attraction is evidenced in other ways than the actual movement of bodies towards one another. It determines the form in which they shall congregate, and that form will be such that each separate body or particle shall be placed so as to obey to the utmost possible extent the attraction of all the other bodies. Thus, if we set a large ball floating in a basin, and a number of smaller ones around it, these smaller ones will range themselves in a row round the larger one, so as to get as close as possible to it.

Just on this principle is it that the surface of a sheet of water is level; every particle of water gets as close to the earth as possible, and thus if by any movement one part is higher than another, the fluid is never at rest till the highest part has sunk down. This is because the attraction of the earth is perfectly overwhelming, compared with the attraction of all other bodies; but if we could

contrive to suspend over the centre of a pool a great ball of many feet diameter, the water immediately under it would be slightly lifted, and it would fall again as the great ball was removed. If we could imagine that the attraction of the earth for water were suddenly to cease, all the water of the pool would fly up and surround our great ball, adhering to it just as iron-filings adhere to a magnet. This supposition is too extravagant, but we can easily imagine a slight disturbance of the perfect equality of the surface, if a very strong attraction be presented to one part of the surface more than another.

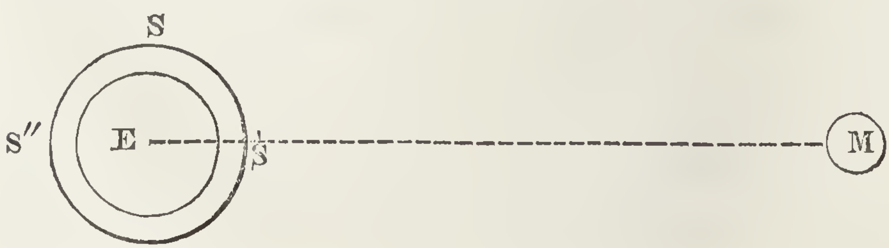
It being clearly understood that attraction is an inherent property of matter of all kinds, only not very evident to us, because we are so accustomed to consider only one body of overwhelming attractive force as the source of attraction, we naturally infer, first, that a large body exerts more attractive force than a smaller one; and, secondly, a nearer more than a remoter one. It is the first of these principles which presents what little difficulty there may be in the realization of the idea of the universality of mutual attraction, the great mass of the earth being so overwhelming in its power. It is the second which prevents the sun and other heavenly bodies of mass enormously greater than that of the earth from interfering with the attractive force of the latter to any

very obvious extent, so that we are not accustomed to consider them, any more than the smaller bodies upon the surface of the earth. The distance of the former, and the smallness of the latter, makes their effects alike generally insensible.

We have seen, however, as in the case of the floating bubbles, how under some circumstances the mutual attraction of small near bodies may be manifested. The earth's attraction does not interfere with horizontal motion, the only resistance which the bubbles meet with is that of the fluid on which they float, a force differing in kind from the earth's attraction; still a force of some power. It is this which has to be overcome by the powerful engines which work our steamers; the earth's attraction does not interfere with their going from Liverpool to New York, but there is a resistance in a horizontal direction which does, the resistance of the water. Now we see that in the case of floating bodies, attraction alone, without oars, sails, or steam, will, though slowly, overcome this resistance. In the case of bodies resting on the ground the resistance is much greater. Two railway carriages standing near together attract one another as strongly as two boats of the same weight, and at the same distance, but the boats will come together, the carriages will not; even a railway offers too much resistance to horizontal motion for the mutual

attraction of the carriages to overcome it. This resistance to movement called in the case of two solid substances in contact, *friction*, is so strong that it may even counteract the force of the earth's attraction itself. A book, for instance, may lie upon a sloping desk, although the earth's attraction would tend to make it slide down, because it is retained by friction. Hundreds of similar examples might be adduced, to show how friction keeps gravity under control. Our only object, however, at present is to show, 1st, That the attraction of other bodies than the earth is always ready to show itself when circumstances permit; and, 2ndly, That there are forces which can overcome even the earth's gravity, and of course what one kind of force will do another of equal power will do. If friction upon a wooden desk will prevent the book from sliding down, some counterforce of attraction, if as strong as friction and acting in the same direction, would equally prevent it upon a desk of ice.

Now let us see what effect the attraction of such a body as the moon can have on the earth, in a manner that shall be sensible to us.



Suppose E to be the earth covered with a certain depth of water, M the moon. Now M and E attract one another, and would approach, and ultimately meet, if they were not held asunder by some force. They are, however, so held asunder we will suppose, that is, the earth as a whole cannot approach the moon or the moon the earth, and we may do this without difficulty, for when a body moves round another in a circle (as the moon does round the earth very nearly) the tendency to approach the central body is just balanced by the *centrifugal* force (see p. 41); but an object on the surface of the earth may move upon it, so far as its movement is not contrary to the earth's attraction. Suppose S to be such an object. It is a matter of indifference so far as the action of the earth's attraction is concerned upon what part of the sphere it rest, but the moon attracts it to S′, the nearest point to itself.

Now S, if a floating body, may go to S′ without any disturbance of the effects of the earth's attraction, but the power which drew S also tends to draw every other particle of matter, even the earth itself. The earth by our supposition is fixed, but the water is moveable. The moon therefore *tends* to heap up all the water at S′. What prevents this? If more water comes, the depth or thickness of the coating of water at that point must be increased, and the last-arrived water must take a

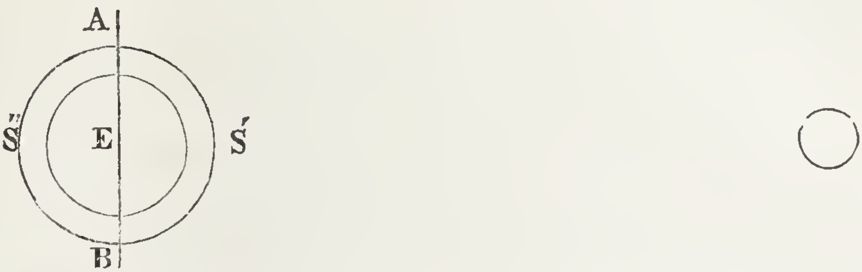
position further from the earth's centre than it formerly had, and it *tends* to force itself back. Here then are two tendencies, one acting against the other: the earth's attraction to keep the water from being heaped up in one particular part, the moon's to draw it all to S′. How will these opposite forces adjust themselves?

It is obvious that the higher this heap is, the greater will be its tendency to disperse itself. The moon may not have power to retain a heap of water twenty feet above the surface of the sphere which the earth's attraction would form, but it may retain a heap of ten feet. At any rate it has some power, which will be exerted in heaping up the water at the side next to it; and if the bodies remain in the same relative position, the sea will be constantly higher on the side next M than elsewhere. The circumstances will not be much altered if the earth turn round, so as to present successively every part to the action of the moon's attraction, and if some land project through the covering of water, there will be a tide upon its shores, rising whenever it comes opposite the moon.

Now let us advance another step towards the actual circumstances as they exist in nature.

Suppose the earth, instead of being absolutely fixed, to be pursuing its course through space at a great speed. It will respond in its movements to the moon's attraction, so as to be slightly deviated

from its course. Every part of the earth feels the moon's influence, but not all equally; those parts nearest the moon will feel it most, and those farthest least.



All the water on one side the line A B will be attracted more strongly than the earth itself, and all on the other side less strongly. Thus a heap will be formed at S′ of the water in the hemisphere next the moon, due not to the moon's whole attractive force, but to the difference of its attractive force at S′ and E. But as E the earth's centre is again more strongly attracted than S″ on the opposite side the earth, the water there will be left behind in a heap, just as if it had been acted upon by a similar attraction in the opposite direction. Thus we see that the moon tends to make two heaps of water at once upon the surface of the sea, the one of those waters which are more attracted than the mass of the earth, the other of those which are less attracted.

The revolution of the earth upon its axis would of course give two tides a day for each point.

Now the moon makes her apparent circuit of

the earth in 24 hours and 48 minutes, and in fact the sea rises twice in that time; so that we have a good ground for supposing that our tides are in some way connected with the inevitable effect of the moon's attraction.

What we have said of the moon and her attractions upon the earth would be equally true of the sun, or indeed any other body sufficiently near the earth to cause an appreciable difference in the force of attraction at the surface and at the centre of the earth.

It is evident, however, that if the distance of any body in the heavens be so great in comparison with the radius of the earth, that the difference of length from this body to the surface and to the centre of the earth be very small compared to the whole distance,—just as one mile in 10 is an important difference, but one mile in 1000 is an insignificant addition,—the earth will be attracted so nearly uniformly in every part, that the raising of the waters will be inappreciable.

It becomes then important to try what are the relative effects of the various heavenly bodies. To do this we must know, first, not only that a greater body exerts more attraction, but in what proportion its attraction increases with its mass; and, secondly, not only that a nearer body exerts more attraction, but in what proportion its attraction increases with its nearness.

The science of astronomy has settled these two points most positively, and lays down these two rules.

1. That the force of attraction exerted by bodies at equal distances is exactly proportional to their masses; that is, a body of twice the mass of another will exert double the attraction.

2. That bodies of equal mass at different distances exert attractive forces which vary *inversely as the squares of their distances;* that is, if in the figure

the distance AB be $\frac{1}{2}$ BC, the attractive force of A on B will be 2 multiplied by 2, or 4 times that of C on B; if AB be $\frac{1}{3}$ of CB, it will be 3 multiplied by 3, or 9 times, and so on.

Let us apply these principles to the attraction which the heavenly bodies exert upon the earth, beginning with a comparison of the sun and moon.

The sun is 28 millions of times greater in mass than the moon, and therefore at the same distance would exert 28 million times the attraction; but its distance from the earth is 400 times as great as that of the moon, and therefore its force is diminished 400 multiplied by 400 (or 160,000) times. Its actual effect therefore is on the whole 28 millions divided by 160 thousands, or 175 times the effect of the moon.

This, however, is the proportion of attraction to the earth itself, considered as one indivisible body; we have now further to ascertain what will be the relative effect of these two bodies, the sun and moon, in elongating the form of the earth by the difference in the force of attraction at its different parts.

To begin with the moon.

The moon is 240,000 miles from the earth, and the radius or half diameter of the earth is 4000 miles, or one 60th of its distance from the moon. The distance then of the centre of the earth from the moon is 60 times the radius, of the nearest side of the earth 59 times the radius, and of the further side 61 times the radius. The force of attraction at the three points will therefore be proportional to the squares of these three numbers, 59, 60, and 61, or 3481, 3600, and 3721, or a difference of 119 between the first and second, and 121 between the second and third.

Now 120 is one 30th of 3600, so the force of attraction is one 30th greater at the nearest point to the moon than it is at the centre, and at the centre it is one 30th greater than at the most distant point.

Now take the sun.

Its distance is 96 millions of miles, or 24 thousand times the radius of the earth. Therefore the nearest point to the sun will be 23,999 times the

radius, the centre 24,000 times the radius, and the farthest point 24,001 times the radius. The squares of these three numbers respectively are 575,952,001, 576,000,000, and 576,048,001, being a difference of 47,999 between the first and second, and 48,001 between the second and third.

Now 48,000 is one 12,000th of 576,000,000, and therefore the attractive forces at the three points in question are as 11,999, 12,000, and 12,001; so that the difference between the surface and centre is only one in 12,000, instead of one in 30, as in the case of the moon.

We may therefore say, that in its relative power to elongate the form of the earth, the sun has only (12,000 divided by 30) one 400th part of the power of the moon.

This great inequality, however, must be lessened by the much greater power due to the mass of the sun, 175 times that of the moon, so that its actual effect upon the raising of tides will be 175 four hundredths of the moon's effect, or nearly in the proportion of 1 to $2\frac{1}{4}$.

If, however, we extend our calculations to the planets, we find their attractive force to be quite insignificant, compared with that of the sun or moon. Jupiter, the largest, is even when nearest to the earth four times the distance of the sun, and only one 1000th of the mass of the latter. Venus, the

nearest, is about one fourth the distance of the sun, but her mass is only one 330,000th of the sun's mass. The other planets are still more inconsiderable as compared with the sun and moon.

The sun and moon then are the only bodies whose attraction can have any appreciable effect in raising the water from the earth, but that each of these bodies must have such an effect is indisputable. We do not say what is the form which the raised water assumes, we only say that such waves of water, as we may call them, do exist, and follow on the earth the sun and moon in their apparent paths through the heavens.

Now the moon makes her apparent circuit in about 24 hours and 48 minutes; therefore the moon's wave will recur twice in that period, or every 12 hours 24 minutes.

The sun makes his circuit in 24 hours, and therefore the sun's wave will recur every 12 hours.

It is evident that these two waves, if they follow (as indeed they do) nearly the same direction on the surface of the earth, must produce the effect of one wave recurring nearly at the periods of the greater of the two, but modified in its height by the smaller wave. Thus, when the summits of the two happen to coincide, the summit of the combined wave will be at the highest; when the hollow

of the smaller wave coincides with the summit of the larger, the summit of the combined wave will be at the lowest.

Now as the sun's wave recurs every 12 hours, and the moon's wave every 12 hours 24 minutes, the sun makes 30 waves in about the same time that the moon makes 29, and if at the first of these 29 the summits of the two coincide, at the 15th the summit of the moon's will coincide with the hollow of the sun's, and at the 29th the summits of the two will again nearly coincide. The height of the first and last will be the sum of the two; that of the middle one the difference of the two.

Here then we have arrived, in our discussion of the effects which must necessarily arise from simple causes, at a point very analogous to the well-known phenomenon of the recurrence of spring and neap tides. The springs, or great tides, occur about every fortnight, at or soon after new and full moon; the neaps, or small tides, in the intermediate weeks.

Now let us look for a moment at the actual position of the sun and moon, when the latter is new and full. When the moon is new we cannot see her, because she is between us and the sun, and her dark side is towards us; but we know that she rises about the same time as the sun, and is in the south at twelve o'clock, the same time as the

sun. The two will therefore be acting nearly in concert in drawing up their respective waves.

When the moon is full she rises near sunset, and is in the south at midnight when the sun is due north. Here they will also act in concert, because the moon's nearest or direct wave will coincide with the sun's farthest or indirect wave, and the same effect will be produced as at new moon.

Take now the intermediate weeks, the moon's "quarterings." The moon rises at midday or midnight, and so is in the east or west when the sun is south or north. Hence the moon's wave will have its summit at a point of the globe at right angles with the sun's wave, and will coincide with the position of the hollow caused by the sun.

The combined action of the sun and moon then upon the waters of our globe must cause a disturbance of them, bearing a great analogy to the variations of spring and neap tides. The analogy is sufficient to convince us that there must be some connexion between the causes we have been considering and the effects we see upon our shores, although there may still remain many apparent discrepancies between the effect and the suspected cause.

CHAPTER III.

MINOR MODIFICATIONS OF THE ATTRACTIVE FORCES.

Tides alternately raised in the northern and southern hemisphere. The cause of diurnal inequality. Declination of the sun and moon. Distance of the sun and moon.

We have now compared the combined action of the sun and moon upon the waters of our globe with the phenomena we are all well acquainted with, of alternate spring and neap tides. We have next to investigate certain other modifications of the attractive force of those bodies, arising from other changes in their position relative to the earth and one another, and compare such modifications with the tides.

If the orbit of the sun and moon were so arranged, that the wave which we have imagined to follow them upon the sea were to move in the same path day after day and month after month; if the orbit of the moon were quite circular, so that the moon should be always at the same distance from the earth; if the orbit of the earth

were quite circular round the sun, so that the sun should be always at the same distance from the earth; all the spring tide waves would be alike, and all the neap tide waves alike; and each series of 29 waves would be exactly like the last series of 29 waves.

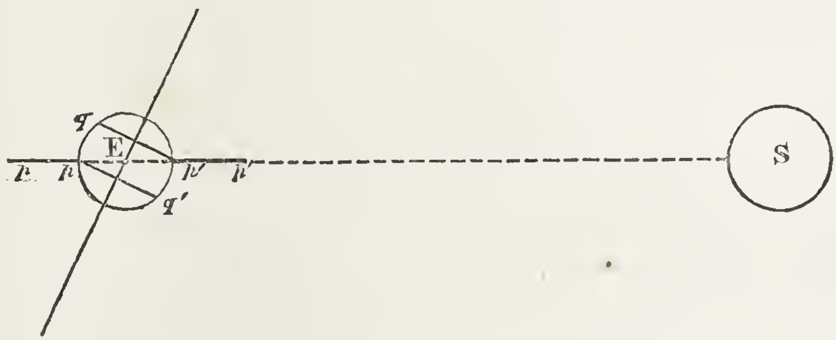
These conditions, however, are not fulfilled, and consequently we may expect some variations in the waves.

In order to understand thoroughly the cause which may thus produce variations, we may with advantage examine rather more in detail than we have hitherto done, the relative movements of the sun, earth, and moon.

Suppose the sun to be represented by an object in the centre of a round table, the earth by a ball, through the centre of which a piece of wire has been thrust to represent its axis. Now pass the ball round the edge of the table, keeping the axis always parallel to its first position; if the ball at the same time turn upon its wire, its motions will exactly represent the motion of the earth round the sun. The point at present especially to be noted is, that the axis of the earth always points in the same direction; in reality, it always points very nearly to the pole star, which is immensely distant, so that the lines drawn from it to the centre of the earth will all seem to be parallel. This peculiarity is well known as the cause of the sea-

sons: we shall see that it also has an effect upon the tides.

Suppose that the ball which represents the earth were at the side of the table opposite to that corner of the room to which its axis points, so that the axis points over the sun; suppose a pencil (p p) held with its point touching the earth and its other end pointing to the sun,



and in the line joining the centres of the earth and sun. Now turn round the earth upon its axis. The pencil will trace a line upon the earth's surface parallel to the equator, and which line in fact will be the tropic of Cancer in the northern hemisphere. Now suppose another pencil (p′ p′) on the same line produced to the other side the earth. This pencil would trace the tropic of Capricorn in the southern hemisphere. These two lines will be the lines which the summits of our tide waves, due to the sun's attraction, follow when the earth is in this position. The two waves will be exactly alike, but one will be in the southern and the other in the northern hemi-

sphere. Moreover, when the earth is in this position, the northern hemisphere is in summer, the southern in winter—as the sun shines so much more directly on the former than on the latter. Further, at the point p it is day, at p′ it is night. The wave will be at its height at p and p′ at the same time; when by the earth's revolution p has got to q and p′ to q′, that is in twelve hours, these two points will not be in the highest part of the wave, but they will feel the influence of the waves at the opposite tropics. These, however, will naturally be much less sensible than the waves 12 hours previously, which they will have felt at their very summits. In such a case, then, we may say that although the point p will have two waves pass over it in 24 hours, that which passes in the day time will be much higher than that which passes at night; while at p′, the night wave will be higher than the day wave.

Now move the ball which represents the earth one quarter round the table.

Here p and p′ will both be on the equator, and

will each trace a line upon the equator by the revolution of the earth. The two waves then will be identical in height and in position, and they will have a similar effect upon all parts.

Next move the ball to the side of the table, exactly opposite to that from which it started.

Here the southern hemisphere is in summer and the northern in winter, and the effect of the unequal waves will be reversed. The southern hemisphere will have its day waves high and its night waves low.

At the fourth quarter the effect will be the same as at the second.

Let us now consider the moon in the same way. The moon moves round the earth in 29 days, and makes the circuit 13 times, while the earth makes one circuit round the sun. Its motion may be likened to that of a point on the circumference of a wheel, of which the earth is the axle. This wheel turns round the earth, at the same time travelling with the earth round the table, and keeping a nearly horizontal position. It does not roll upon the table, but lies with one

half its flat side on the table while it turns. It is not always quite horizontal (that is, in astronomical terms, in the plane of the ecliptic), being inclined to it at an angle of upwards of 5 degrees, but for our present purpose it may be assumed to be quite horizontal. Now it will be seen that the revolution of the earth upon its axis will cause the point p, if supposed in the line between the moon and earth instead of between the sun and earth, to trace lines encircling the earth, similar to those traced in the case of the sun. At new or full moon the line will coincide with the sun's line. At the quarters it will coincide with the line made by the sun three months previously. In other words, at spring tides the effects of sun and moon are the same throughout the year. At neaps, in summer and winter the moon makes the circuit of the equator, and in spring and autumn that of the tropics.

Thus then we see that at *new and full moon*, during summer and during winter, the sun and moon exert their attractive forces together upon alternate belts of the earth's surface, so that the consecutive waves caused by these attractions, although recurring at the regular times, or nearly so, will be in themselves different. In spring and autumn, the attractions are exerted upon the equator each time, consequently the consecutive waves will be nearly similar.

At the *moon's quarters,* when the sun and moon act at right angles to one another, in spring and autumn the moon will be on the tropics and the sun on the equator, and in summer and winter the moon will be in the equator and the sun in the tropics.

If, therefore, these varying causes have any effect upon our tides, we shall find in summer and winter alternate spring tides high and low, and neap tides nearly regular. In spring and autumn we shall find spring tides regular, and neap tides alternately varying.

This we find to be confirmed by observation. We shall have occasion hereafter to examine this point more in detail. For the present, we merely remark that there is enough of sensible effect to enable us to identify it with the cause. It is called the *diurnal inequality* of the tide.

We now come to another cause of variation, also depending upon the different part of the earth's surface on which the sun or moon exerts its attraction. The position in which the earth stands with regard to the sun or moon is described astronomically by the term "declination" of the sun or moon. It means simply the latitude of the point on the earth's surface at which the sun or moon shines down vertically. Thus, on the 21st of March the sun shines down vertically

on the equator. The sun's declination is then zero.

On the 21st of June it shines down vertically on the tropic of Cancer, and the declination is then $23\frac{1}{2}$ degrees north, that being the latitude of the tropic. On the 21st of December it shines down vertically on the tropic of Capricorn, and its declination is then $23\frac{1}{2}$ degrees south. The declination of the moon, when new or full, is always nearly the same as that of the sun. At the equinoxes of March and September it is never more than $5\frac{1}{4}$ degrees either south or north. At the period of midsummer it is never more than $28\frac{3}{4}$ degrees nor less than $18\frac{1}{4}$ degrees north. At midwinter it is between $18\frac{1}{4}$ and $28\frac{3}{4}$ south. When in the quarters, the declination is great in spring and autumn, and small in winter and summer, within the same limits.

After this explanation, we shall make use of the technical expression "declination" freely, and now proceed to explain the second variation of the tides, depending on declination.

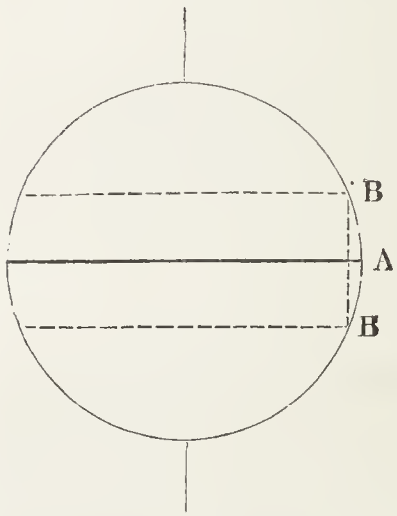
The earth revolves on its axis once in 24 hours; all parts, therefore, of the surface of the earth are moving with a speed which varies according to their distance from the axis; the equator at the greatest speed; while an object at one of the poles merely turns round once in 24 hours, without shifting its place at all.

We have now to examine the effects of this rotatory motion, and in doing so we shall again have recourse to a more familiar example.

Suppose then a weight tied to a string, and whirled round with considerable velocity. The string is kept stretched, and the force which stretches it is evidenced by the tightness with which it will wrap itself round the finger. Now if this string be lengthened so as to make the weight at the end of it describe a larger circle, and it be compelled to make the same number of revolutions in a certain time notwithstanding its increased length, the strain upon the string will be increased, and it may even break. The force which tends to stretch the string, and at last is sufficiently powerful to break it, is called the *centrifugal force.* It acts in all cases of revolving bodies, tending to make them fly from the centres round which they turn. It is increased with the speed of the revolution, and also with the distance from the centre of revolution.

Now objects on the surface of the earth are acted upon by centrifugal force, and the attraction to the centre of the earth, like a string, prevents the surface from flying away. Centrifugal force has had some effect even upon the form of the earth. In the course of countless ages it has changed it from a sphere to a spheroid, i. e. a flattened sphere having the axis about which it

rotates, shorter than the equatorial axis. And the centrifugal force still acts, and is greatest at the equator, which is farthest from the earth's axis, and it diminishes gradually in approaching the poles, which are on the axis, and where there is no centrifugal force. It is evidently greater at the equator (A) than at the tropic (B), because the curve of the earth brings B a little nearer to the axis than A. Now observe that this centrifugal force acts in nearly the same direction as the attraction of the heavenly bodies, and we may naturally expect that where the attraction of the heavenly bodies is assisted the most by centrifugal force, there the effect will be greatest. Consequently the tide wave, whose summit is in the equator, is greater than one whose summit is on one or the other side the equator. It depends in fact upon the "declination" of the sun and moon; being greatest when the declination is zero, and least when the declination is greatest, whether north or south.



Now equinoctial tides are well known to be the highest. At the equinoxes sun and moon act in

concert upon the equator, where they have the greatest effect.

We have now to refer to one more cause of variation, viz. the varying distances of the sun and moon.

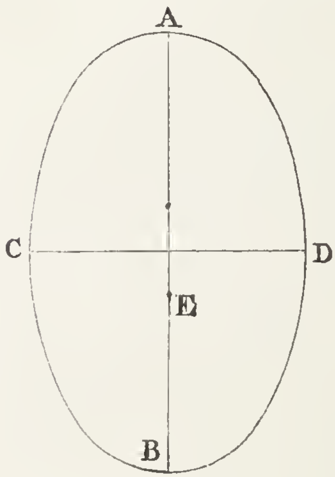
The orbit of the earth round the sun is not quite circular; it is an ellipse, and at one period of the year the sun is $\frac{1}{30}$ nearer than at another. At its nearest point, therefore, its force of attraction will be to its force at its most distant point in the proportion of 841 to 900, or nearly 14 to 15. While the sun is nearer to us, then we may expect slightly higher tides.

The moon's effects in this respect are more important. Her orbit is much more elliptical. Her greatest and least distances from the earth are in the proportion of nearly 8 to 7, her attractive force at her greatest and least distances, therefore, will be in the proportion of 64 to 49, or nearly 4 to 3.

Moreover the moon goes through all her changes of distance from the earth in about a month; that is, once in every month she is at her greatest distance, and once at her least.

The variations, however, do not coincide with the months, as measured from new moon to new moon, but their period is rather shorter. This will be made more clear by the examination of another peculiarity in the moon's motions.

The form of the moon's orbit is an ellipse, as we have before said. The two diameters of an ellipse, which respectively divide it in length and breadth, A B and C D, are called its major and minor axes. Now the motion of the moon is such, that in following the earth round the sun, the major axis of the ellipse always points in nearly the same direction on the heavens, quite irrespective of the direction of the sun. Thus, if in January the end A of the major axis is pointing towards the sun, and the moon when new is at her greatest distance from the earth, represented by E in the figure, in July the end B of the major axis will point to the sun (or nearly so), and the new moon will be at her least distance from the earth.



At the equinoxes the minor axis will point towards the sun, and the new moon will be at a medium distance. From this we see that the effect of the moon's greater or less attraction, caused by her varying distance, acts upon the tide successively in all states; at one time increasing the neap tides, at another the springs.

We have said that the major axis maintains *nearly* the same direction. It is not quite the

same. It turns a little every day, so that at the end of a year, when the earth returns to the same place, the major axis of the moon's orbit is pointing in a direction about 40 degrees different from that in which it was at the beginning. Thus in 9 years it will have changed 360 degrees, or returned to its original direction.

CHAPTER IV.

PREDICTION OF TIDES.

Recapitulation of the coincidence of the tides with the varying positions of the sun and moon. Newton. Bernoulli. Prediction of tides. Sir J. W. Lubbock's method. Admiralty tide tables. Effects of the changing positions of the sun and moon on the time of tide. Also capable of prediction.

We have now explained what are the attractive forces, with their various modifications of position, distance, &c., which affect to any appreciable extent the surface of our globe differently from the mass of the globe itself, and we have not hesitated to attribute to these attractions the phenomena of the rise and fall of the tide. Though we have only reached the first step of the explanation, we have thought the evidence quite sufficient to prove at least a connexion. For we have seen,

First, that the average periods of the return of high water at any place are the same as those in which the moon makes her apparent circuit of the heavens.

Secondly, that on the one hand the height of the

tide varies considerably twice in each month; and on the other, that twice in each month the sun is attracting in the same line with the moon, and twice in the transverse direction.

Thirdly, that on the one hand consecutive tides are of unequal heights; and on the other, that alternate tides are raised in different hemispheres, north or south of the equator, and so might naturally be differently apprehended by us.

Fourthly, that on the one hand there are variations in the heights of the tides not accounted for by the two last causes; and on the other, that the effect of the tidal force of attraction varies according as it acts on a circle on the earth's surface, nearer to or farther from the equator; or as the distance of the attracting body itself is greater or less.

We shall see farther on, that, although less obvious, the minor variations last mentioned are as regular in following the changes in the position of the heavenly bodies, as are the greater variations known in spring and neap tides.

This was the state to which Sir Isaac Newton brought the science of the tides, and a wonderful step it was.

From a theory deduced from astronomical observations applied to a terrestrial phenomenon, he showed the *primary* cause of the tides. He had not the materials for making another step.

Terrible rows of figures of times and heights observed in many places, besides a more perfect knowledge of some other branches of science, especially hydraulics, were required to go further.

Newton, in fact, told us how the tides are produced. It is yet reserved for future times to show with the same clearness how they come to our coasts, and what changes they undergo before becoming evident to us. Newton's theory, however, was sufficient to enable his more immediate successors to take another very important practical step, namely, to *predict* tides.

The first person who attempted this was Daniel Bernoulli, an eminent French mathematician, who in 1740 published a treatise on the subject, which divided the prize of the French Academy with treatises on the same subject and same date, by Maclaurin the Scotchman, and Euler the Swiss.

Bernoulli's general principle has been followed by all other calculators, at least by all who have published their methods; but until Sir John W. Lubbock about 25 years since took up the subject, and calculated upon a published formula, from time to time extended and improved, tide tables for various ports, the best tables were formed by rules kept jealously secret by their

discoverers. Among the most perfect of these are the tables for Liverpool published by Mr. Holden.

The method followed by Sir John Lubbock was in principle the following. He took a series of observations extending over 19 years; that being the period in which the moon returns into the same position relative to the sun in all respects, and consequently containing a cycle of all varieties of tides; all amounts of declination, distance, &c., for the different directions of the sun and moon.

This gave him about 14,000 observations as his materials.

He divided these 14,000 into 24 groups, the first containing all those tides which occurred on the day of new or full moon, when the moon crossed the meridian, or became exactly south, between twelve and half-past twelve; the second group contained the tides of the days when the moon was south between half-past twelve and one; the third between one and half-past, and so on for the 12 hours.

Each of these 24 groups contained about 580 observations.

Striking an average of all the heights in each group, he found the height to which, *on an average*, all tides which occur on the day of a certain time of transit of the moon rise, which is

as much as to say, that when the sun and moon have their mean declination, and are at their mean distance from the earth, such will be the height of the tide at the different periods of the moon's age.

His next process was to place against the date of each tide, in each group of 580, the declination of the moon when in the meridian on that day. He then divided each group into 11 subdivisions, each subdivision consisting of those tides corresponding to a declination of 0° to 3°, 3° to 6°, 6° to 9°, &c., up to 27° to 30°. He then took the averages of the heights in each of these subdivisions, and so found how much the tide at any given period of the moon's age would be affected by the moon's declination. With the moon on the equator the height would be so much; and the difference would be so much for each three degrees of declination.

Next he took the same 24 groups of 580 tides, and subdivided them according to the moon's distance from the earth at the time each occurred, making a subdivision for each minute of parallax [1].

[1] Astronomical tables give the distance of the sun and moon, not in so many miles, but by their *parallax*, that is, the size which half the diameter of the earth would appear to be to a person standing on the sun or moon. This would evidently be larger as the sun or moon became nearer. The moon's parallax varies from 54 to 61 *minutes*; the sun's from 8·66 to 8·94 *seconds*.

From this he found how much the moon's distance made the height of the tide vary from the mean height at any given age of the moon.

The same process was gone through with the sun's declination and parallax; and also the declination tables were again subdivided into north and south declinations, or day and night tides, to show how much inequality there was between them for each 3 degrees of declination.

Thus 7 tables were obtained as follows:—

I. The average height of the tide corresponding to any half hour of the moon's transit.

II. The variation from this average caused by the moon's declination.

III. The variation caused by the moon's parallax.

IV. The variation caused by the sun's declination.

V. The variation caused by the sun's parallax.

VI. The inequality between two consecutive tides caused by the moon being alternately north and south of the equator.

VII. The same inequality dependent upon the sun.

With these tables therefore, a set of which may be found in the Companion to the British Almanack for 1837, the height of the tide may be

predicted for any future day for any place to which the tables are applicable in the following manner.

The Nautical Almanack gives the time of the moon's transit for the day in question. Table I. gives the average height corresponding to such time of transit. The Nautical Almanack further gives the moon's declination for that day. Table II. gives a correction of a few inches to be made to the height given in Table I. In the same way Tables III., IV., and V. give further small corrections according to the parallax and declination for the day as given in the Almanack, and then a height is found which is half-way between the morning and evening tides of that day. Tables VI. and VII. give the correction to be made according as the higher or lower tide of the day is wanted.

This mode of calculation having been compared with observation, it was found to have indicated with remarkable precision the changes which did actually follow in the various heights of the tides. Such discrepancies as appeared were made the groundwork of renewed study, and some corrections were made, especially that in calculating the tide for a certain day, the time of the moon's transit of 2 or 3 days previous was taken as the starting-point of the calculation.

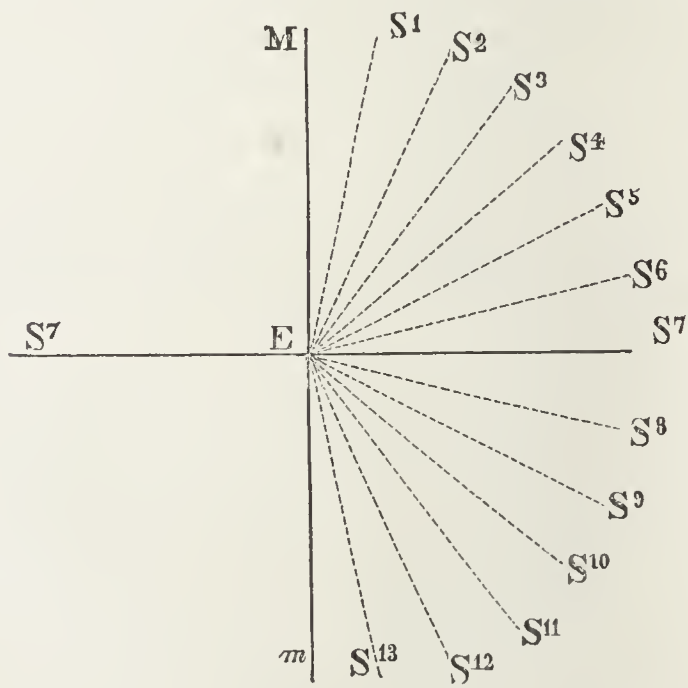
In this manner tides have been predicted for

every day of the year for all ports at which a sufficient number of observations had been made to found the tables upon, and the predictions have been verified in a most remarkable manner.

Two causes not taken account of were found to influence the height of the tide. First, the weight of the atmosphere as indicated by the barometer, and the amount of variation from this cause has been ascertained at various places; secondly, the effect of the wind, which has not yet been reduced to fixed laws, but which when in certain directions raises, and in others lowers the tide.

With the exception of the irregularities consequent on these two causes which are not calculable beforehand, the Admiralty tide tables give every year the exact height of the tide for any day at 21 different ports, and approximately by addition or deduction from one of the standard 21 ports, for a great number of others. The time of high water is also given, so that a captain making for a certain port can tell by his tables at what time he can safely enter, and so takes care to keep well out to sea till his tables warn him he may safely approach. But for these tables he might often have to lie at anchor off a lee-shore in a gale for hours, while his destination, though within half a mile, is unapproachable by his ship. Warned by his tables, however, he will be able to take another tack in the safe open sea.

Hitherto we have only spoken of the average period of the return of the tides which is every 12 hours and 24 minutes, the time of the moon's apparent half revolution, but it must be remembered, that although the combined solar and lunar wave follows in its main features the influences of the moon, yet that as the sun materially modifies the height, so it will have an effect upon the time. The way in which this is brought about may be made clear. Suppose E M to be the direction of



the moon's attractions on the day when it is new or full. On that day the sun's attraction will act in the same direction. On the following day the moon will be 48 minutes later than the sun, so that the sun will have brought its wave to a

summit 48 minutes before the moon's arrives; the combined wave therefore will be rather sooner than the moon's would be alone. The second and third days the sun's effect in accelerating the tide will increase; but let us see what will be its effect when it is in the direction S7, or at neap tides. If the sun acted in the direction S7 alone, its effect in accelerating the time of tide would go on increasing, but there is an equal and opposite effect in the direction E S7, which retards as much as the first accelerates, and therefore at neap tides the time is that due to the moon alone, the sun's effect being entirely neutralized. As the tide passes the neap, the opposite effect will be produced, the retarding force of S will be predominant, and the tide will be kept back until the next spring, when it will be again at its regular time. Now it will be evident that as these variations in the time depend upon the relative forces of the sun and moon, the amount of variation will be modified by the changes of position and distance, that is, of declination and parallax.

The following table will illustrate the effect of the sun in accelerating the tide from springs to neaps, and in retarding it from neaps to springs, and how at neaps as well as springs it is coincident with the lunar wave.

It gives the time of high water at Liverpool in the month of December, 1853, from the full moon on the 16th to the new moon on the 30th.

Column I. is the time of the lunar tide, varying from 44 to 51 minutes daily.

Column II. that of the actual combined solar and lunar tides.

Column III. the difference from day to day of the time of the actual tide.

Column IV. the amount which the actual tide is *before* the lunar tide.

Column V. the amount which the actual tide is *behind* the lunar tide.

Day.	I.	II.	III.	IV.	V.	
○ 15	11·6	11·6		0·0		Spring.
16	11·33	11·40	34		0·7	
17	12·23	12·13	33	0 10		
18	1·13	12·50	37	0·23		
19	2·03	1·26	36	0·37		
20	2·51	2·8	42	0·43		
21	3·38	2·48	40	0·50		
22	4·24	3·35	47	0·49		
☾ 23	5·08	4·27	52	0·41		Neap.
24	5·54	5·33	56	0·21		
25	6·41	6·39	66	0·02		
26	7·31	7·47	68		0·16	
27	8·26	8·46	59		0·20	
28	9·26	9·41	55		0·15	
29	10·30	10 33	52		0·3	
● 30	11·36	11·28	55	0·8		Spring.

Now here it will be observed, that from two days after spring tide till two days after neap tide, the differences are in Column IV., or the actual tide is in advance of the lunar tide. After that, the differences are for four days in the Column V.,

or the actual tide is in arrear of the lunar tide. The irregularities are consequent upon the changes of declination and parallax which take place within the fortnight. Now it is clear that these variations in the times, being dependent upon the same causes as the variations in the heights of the tides, can be treated in the same manner as the observations of height. Each observation being referred to its group, tables may be formed from which the time of any future tide may be predicted.

This has been done, and the result has been equally successful with the result of the predictions of height.

The tables give the height and time of high water for every tide.

The level and time of low water are equally capable of being predicted in the same manner, but although as interesting in a scientific point of view, they are practically less useful, and the mass of observations collected is much smaller. Of late years, however, tidal observations have become more universal in all situations where facilities are afforded for making them; they are made upon an uniform scientific system; the general results are recorded upon all recent charts; and materials are being from year to year accumulated, which will enable the tables to be extended, and their precision increased.

CHAPTER V.

THE TIDE WAVE IN THEORY.

Theories of the tides. Newton and Bernoulli. La Place. Airy's wave theory. Waves, their general laws. Wind waves. Tide wave. Scott Russell's experiments. Professor Airy's application to the tides. Laws of movement and magnitude of waves. Solar and lunar waves independent of each other.

It will be seen that although the theory of the tides has been brought to such a precision, that we are able to predict how the tide will rise at certain places with almost as much accuracy as an astronomer can predict the place of a planet on a certain day, there is another view of the tidal phenomena which we have not yet touched upon. We have traced all the tidal phenomena which have been observed, say, at Liverpool, to their ultimate causes, and we predict their return, upon the principle that a repetition of the same causes will in future produce similar effects.

But it may naturally be said, "All that you have done hitherto has been to explain and predict the changes that occur from time to time at the

same place. Can you equally well explain the variations of the tide which occur at the same time in different places?" To this we are obliged to reply, No. Some advances have been made towards it, but up to the present time, all that we can do is to offer, with a fair chance of being right, an explanation of the cause of a phenomenon, after the existence of the phenomenon itself has been proved.

For instance, if we have an opportunity of observing the rise and fall of the tide at any given point of the coast for a few days, we can, with a very fair approximation to success, predict how the tide will rise and fall at the same point for years to come; but it will not enable us to say how the tide is rising and falling on the very same day at a point 20 miles distant. Its time may be, and often is two or three hours earlier or later; and the height to which it rises may be half or double that at the place we are observing. The variation from time to time we know; the variation from place to place we are very ignorant of. The one depends upon the primary cause, which is astronomical and precise, the other depends upon certain terrestrial causes, which are very imperfectly understood; more from the want of observations, and the difficulty of making and collecting them, than from want of knowledge of the principles which are at work.

We have spoken of the immediate effect of the attraction of the heavenly bodies as a wave or tide, using the words according as one or the other in its ordinary application appeared best adapted to the ideas which we wished to convey. Had we been more desirous of scientific precision than of popular explanation, we should have introduced some new term to represent the combined effect, whatever it may be, of the attractions of the heavenly bodies upon the part of the earth's surface where that effect is greatest.

This effect would be a wave, or heaping up of the waters at the point immediately under the sun and moon, if the earth stood still long enough for all the forces to be brought to bear. But this is not the case. The surface of the earth at the equator is travelling on at a speed of 1000 miles an hour, owing to the rotation upon its axis, so that it is only for an instant of time that any point is exposed to the full action of the attractive force. There can never be the *full* effect; only a *tendency* to it; some disturbance of the level of the water, influenced and modified by various circumstances.

Also, with regard to the time which is required for the attractive forces to bring about their greatest effect, we know that the effect cannot be instantaneous; some time must be required, and during this time the earth is proceeding on its course, and the wave, which if the earth had not

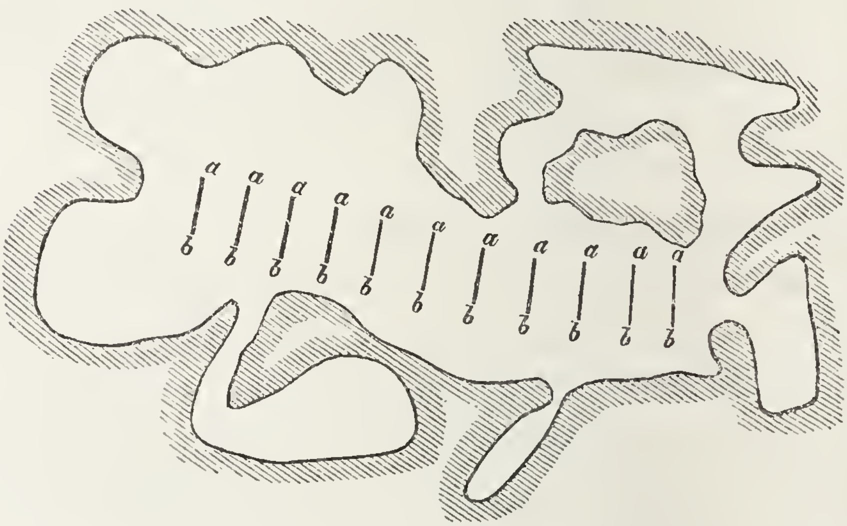
been rotating would have been immediately under the attracting body, will be some distance behind it; the distance being the space through which the earth has moved in the time necessary to raise the wave. Now if the earth were a globe covered with an uniform thickness of water, mathematicians would be able to calculate the height of the wave of water which would be raised, and of its position with respect to the sun and moon.

This has been done, but as might be expected, without any very direct practical result, because the calculations were made for a globe rather unlike ours. There have been some results from these labours; for there is in some points a correspondence between facts and theory which throws light on both, but they have not enabled us to lay our finger upon any part of the map of the world, and say, "At that point, though no one has ever observed the fact, we are sure that the tide rises so much, and that it is high water at such a time of the day."

Perhaps the best way of giving an idea of the kind of investigation which would be required to attain such an object will be to take an illustration.

Suppose then a tub or trough of water of some regular figure—square, round, or oval. Suppose that a flat board is moved slowly and regularly,

backwards and forwards, broadways in the water. The surface of the water will rise in waves with the motion of the board. The oscillations will appear to be irregular at first, but in a short time they will be as regular as the movement of the board, and the rise and fall at any particular point will regularly follow them. In this case the effect follows so immediately from the cause, that it will scarcely be imagined that the tracing of the one to the other is a very complicated work. But suppose instead of a regularly formed tub we have a



vessel of this shape, in which the board is constantly moving. After a time, no doubt, the oscillations of the water in any point of the irregular sides will respond to the regular movement of the board, but who could pretend to trace them? Who could possibly say how the various bends, hollows, protuberances, narrowings, and widenings

will affect the movements of the water, simple as it may be at first? still no one can doubt that all will be affected, and that every movement of the board will be responded to by some corresponding movement, even in the most intricate recesses.

Now, in point of fact, the earth on which the philosophers have reasoned, is as unlike the earth on which we live as the square tub is unlike the distorted figure we have subsequently depicted; and the case of the earth is far more complicated to begin with, even in its supposed calculable form.

Thus we see that it is, at present at least, impracticable to trace out all the steps by which the disturbance of the sea's surface results ultimately in the ebb and flow, such as we see it. We can get no further than the fact, that one is the *primary cause*, the other the *ultimate effect*. We ought not, however, to pass over without some notice the principal attempts which have been made to investigate the real effect of the attractions upon the earth. Sir Isaac Newton calculated what would be the height of the tide which the sun's attraction would raise at the equator, if it had its full effect. He found it about 2 feet. In his time the moon's mass was not known, and his calculation of the tide due to her attraction was incorrect. He supposed it 8 feet 8 inches. *We* know that her influence is $2\frac{1}{4}$ times that of the

sun, so her tide would on this supposition be $4\frac{1}{2}$ feet high, and the spring and neap tides being respectively the sum and difference of these two, would be $6\frac{1}{2}$ and $2\frac{1}{2}$ feet.

But as we have before seen, this tide could not be produced, even if the earth were entirely covered with water, because the rotatory movement would always prevent the attractive forces producing their full effect.

Bernoulli followed Newton, and extended the calculations upon the same basis, but they are useful only in giving the relative tendencies of the two bodies in their different positions; they give nothing positive in the way of actual dimensions.

La Place, at the latter end of the last century, proposed another view of the subject, based still upon attraction; but instead of calculating the tendency of the water to rise from the earth towards the attracting body, and thereby occasioning a movement of water from each side to supply its place, he rather took the horizontal movement of the water as the primary object of his calculations, and supposed the rise of the surface due to the meeting of two such currents just under the sun or moon. This horizontal movement is caused by the tendency which all particles of water between S and S′ have (figure, p. 22) to move towards S′, and between S and S″

to move towards S″. This theory was worked out with the most consummate skill, and certainly enables us to approach nearer to an explanation of the actual circumstances than Newton's supposition did, but it has been equally unavailing in any practical way, and owing to great mathematical difficulties which it presents, has not, in the opinion of Dr. Whewell, done so much as Newton's and Bernoulli's theory towards facilitating that portion of the science which is reducible to mathematical calculation, viz. the prediction of future tides at a place where the past ones have been observed.

Another view has been proposed by Mr. Airy, the present astronomer royal, and has been fully detailed in his article on "Tides and Waves" in the Encyclopædia Metropolitana. He treats the tide from its formation under the attractive forces as a *wave*, using, like La Place, the horizontal current between S and S′ as the groundwork of his calculations.

This theory not only gives an explanation of many ascertained facts, but it is beautiful and interesting as presenting to us the tide from its first formation in the form in which we afterwards find it, a *wave* subject to fixed and known laws in its motions and magnitude after it has become independent of the attraction of the heavenly bodies.

The progress of the tides from that part of the ocean where they are first produced had long been likened to that of a wave; and that curved surface of water which, commencing at one low water, passes over the summit of the tide down to the next low water, had been denominated the *tide wave.*

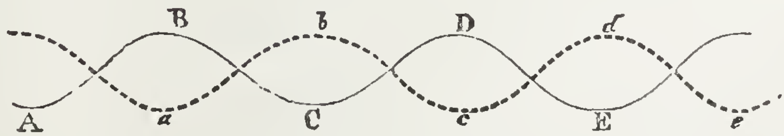
The analogy of its form to that of an ordinary wave is easily seen. If a pole stand in some part of the sea where the waves do not break, the water will rise and fall upon the pole as the wave passes by it, just as the tide does, except that the high water will return every few seconds instead of only twice a day. The tide wave is so long that it takes $12\frac{1}{2}$ hours to move its own length, but it is not the less a true wave.

This enormous length, however, makes it so very different a thing from the waves which we ordinarily see raised by the wind, that it would not be right at once to assume that it is governed by the same laws in its formation and motion.

Until a few years ago we were very ignorant of the actual movement of the particles of water in waves. The onward movement of the wave itself is evident enough, but it is equally evident that the water itself does not move forward with the wave. In other words, the wave as it moves onward preserves its identity as a wave, but the

water of which it is formed is being each instant changed. The actual particles of water merely move up and down, or nearly so. This may be evidenced in many ways. A ship continues her course at sea pretty much in the same way, whether the sea is calm or disturbed. She mounts over the waves without appearing to be materially checked by them; and on the other hand, when she is running before the wind in the same direction as the waves themselves, they pass her without materially accelerating her onward motion. A little consideration will make it clear to any one who may not previously have considered the matter, that the motion of a wave is one thing, and that of the water in which the waves are formed is quite another thing.

It is quite evident, however, that there must be some horizontal movement in the particles of water from this consideration.



Let A B C D E be the surface of three waves. After a certain interval of time the same waves will have taken the position *a b c d e*, and objects floating at B and C will have been lowered to *a* and raised to *b*. The space between B and *a* has been emptied of water, that between C and *b* has

been filled. A mere vertical movement cannot have effected this, for water has actually gone away from under B, and water has actually been brought over C.

A series of very beautiful experiments was made in the years 1837-8, by Mr. John Scott Russell, for the British Association, with the view of determining these movements, and these experiments have curiously enough thrown great light upon the movements of the seas which are caused by the attractions of the heavenly bodies and ultimately result in our tides.

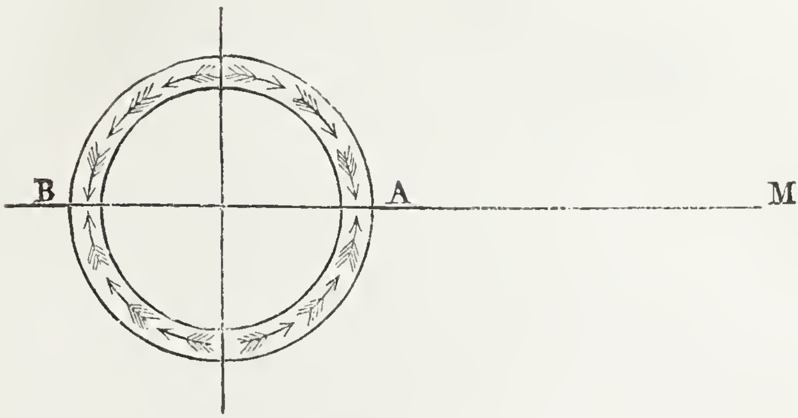
Let us look at the ordinary cause of waves upon the surface of water—wind. How does this act? It is a force acting in a horizontal direction upon the surface of the water. By the friction of the moving air upon the motionless water, the former has a tendency to drag the latter after it. It does so to a certain extent till a little heap of water is raised; this heap, however, has a tendency downwards by its gravity, and so communicates some slight motion to the particles of water in its neighbourhood, and an oscillating movement is produced among them. Heaped up by the wind in the first instance, they next settle down by their own weight, but they go by their impetus a little farther down than the exact level of the water, then rise again a little too high, and so on. If the wind drops, the water soon regains its per-

fectly flat surface; but if it continues, the ripples present an irregular surface, on which the wind acts more powerfully, and the ripples increase to waves. Now observe that these waves, so stupendous and awful as they may become in their up and down movement, are entirely caused by a horizontal force on the surface of the water. A few inches down when the ripple begins, and a few feet down in the height of the storm, there is no motion.

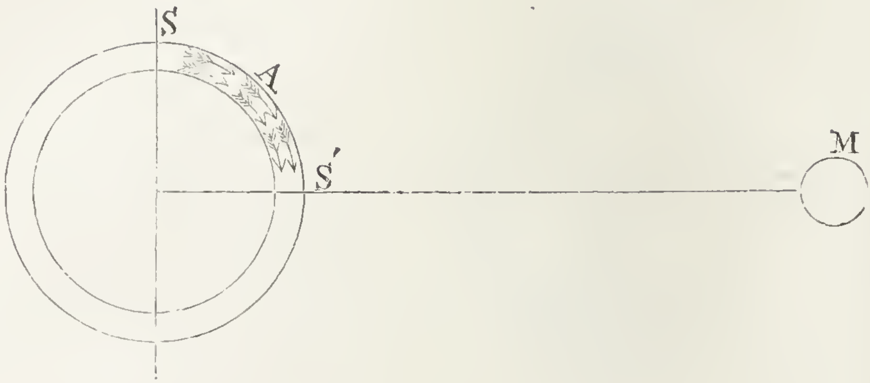
But suppose that instead of the wind acting upon the surface of the water we had a force which moved the water forward a little for its whole depth. Suppose, for instance, a trough 20 feet long, a foot wide, and a few inches deep, full of water; suppose a flat upright board just fitting the trough to be placed across it. Now if this board be moved forward six inches, it is plain that the whole body of water in front of it will have an onward force communicated to it to that extent, but it will be first felt close to the board, where a wave will be raised, which will consist of a quantity of water equal to that which has been disturbed by the movement of the board, and this wave will roll along the whole length of the trough, diminishing, it is true, in height, but still it will be for some time sensible. Now observe first the difference in the cause of this wave from the cause of a wave of the sea. Both are raised

by horizontal forces, but the one by a force acting on the surface only, the other by a force uniform from top to bottom of the trough. Next observe the different effects. The wind waves follow one after another, one wave assisting in giving to the water the oscillating motion which maintains the next, and the whole surface is put into commotion. In the case of the trough wave, however, no second wave is produced; it travels on its way alone, and when it has passed, the water behind it is tranquil. Mr. Russell has denominated this solitary wave, the primary wave or wave of the first order; the wind waves, waves of the second order. Both are obviously *waves* in the common acceptation of the term; they have some characteristics in common, and in some respects differ; the great difference being this, that in the wave of the first order the force which produces it, and the motion of the particles of water, are uniform from top to bottom of the channel; in the wave of the second order the force is on the surface, and at the surface the immediate effect, the motion of the water, is greatest; and gradually lessens in descending, till it entirely disappears.

The motions of these two kinds of waves have been minutely investigated, especially those of the waves of the first order, both theoretically and experimentally. We have now to show their connexion with the tides.



Dividing the circumference of the earth into four quarters, it will be seen that in each of the four quarters the attraction of the sun or moon is acting upon the whole depth of the sea, to draw it towards the points of greatest attraction at A and B. The attraction of the moon, if acting alone, would be towards itself, but combined with that of the earth the resultant force and the actual motion are parallel to the surface of the earth or horizontal. Now here is the exact condition under which a wave of the first order is produced, and the force of attraction being known, the mathematician has the means of deducing all the dimensions and other particulars of the wave. Such is the foundation of the wave theory of the tides. Let us for a moment recapitulate the circumstances of the formation of a tide.



The tendency of the moon's attraction is to draw all the water from S towards S′. It commences this operation, it has not time to complete it, but it gives to the water just that kind of motion which raises a solitary wave of the first order upon the surface. The attractive force moves on, changes its position, in a few hours tends even in a totally different direction; but the wave has been formed, and it follows the laws of all other waves, it travels along over the sea, setting the water in motion as it goes, but when it has passed leaving the water again still. It travels on, raising itself in all parts of the sea at one point after another, and washing the coasts of the continents on its way. The water therefore which we see rising on our coasts is not itself being at that moment attracted to the moon, but is the great wave which was at some past time

and at some distant part of the earth formed by the attraction of the water of the sea, not upwards from the earth, but towards the point of the earth's surface nearest to the moon.

This great wave would follow the moon round and round the earth, if its path were not interrupted by continents; but although its motion is interrupted, it is not stopped. Originally impelled towards the moon, it is equally capable of moving in any other direction. It has received the motive power, and retains it after the attractive forces have passed to some other point.

If the surface of the globe were uninterrupted sea, the wave would follow the moon at a certain distance round and round the earth. Its height would then be, according to the calculations of Professor Airy, nearly two feet at spring tides, and about nine inches at neaps; and it would appear from the best knowledge that we have of the rise of tide in the open sea, that it is actually about this amount. It is from terrestrial causes, the influence of the irregular bed of the ocean near land, and the shores of the land themselves, that this originally small wave attains the dimensions of our tides.

Mr. Scott Russell's experiments upon waves of the first order established the two following principles:—

1st. That the speed at which a wave travels

when its original moving force is removed, depends upon the depth of water, and is that which is scientifically called "the velocity due to half the depth." We will explain this: If a hole were pierced in the middle of the side of a cistern full of water, the water would rush out of the hole with the same velocity that a wave would travel along the cistern. The rate of a wave's motion does not depend in any way upon the height of the wave, except in so far as this gives an additional depth to the water. This in a sea 20 or 30 thousand feet deep is inappreciable, but in a shallow channel, such as a river, there may be a tide wave of 30 or 40 feet raised upon a low water channel of 10 feet deep. In such a case, the height of the wave is an important element in determining its rate of progress.

The second important principle established by Mr. Russell's experiments is that the height of the wave is very dependent upon the form of the channel. Where the channel gradually becomes narrower and shallower, the wave increases in height as it progresses. This will account for the great difference in the height of the tide on different parts of the same coast and from its theoretical height in the open sea.

Another principle to be borne in mind is this. Two waves may coexist in the same fluid, and each will maintain its own movements, indepen-

dent of the other. We have shown that the tide is composed of two distinct waves, the lunar and the solar. They manifest themselves indeed to us as one wave, but that they are independent is proved by the fact, that we find certain varieties in the tides which can only be due to the two waves following somewhat different changes and movements. Thus in some places the range of the neap tides will be three-fourths that of the springs; in others only one-fourth. In the former of these cases, the height of the solar wave is only one-seventh of that of the lunar wave; in the latter it is three-fifths. Again, the inequality of time of high water, owing to the different distances in the summits of the two waves, explained at p. 54, varies materially in different places. At Liverpool the greatest difference between the actual tide and the lunar tide is 50 minutes; on some parts of the coast of France 100 minutes. Now these facts can only be accounted for upon the supposition that the two waves, lunar and solar, are differently acted upon in their progress, both as to their speed and their changes of form and dimensions by the circumstances of depth and form of channel. That they should be so differently acted upon is natural, because one is rather more perfectly a wave of the first order than the other. The sun acts more uniformly upon the whole depth of water than the moon, owing to his

much greater distance, so that the solar wave will probably follow more truly the laws of motion of a wave of the first order. In certain cases this diversity of the two waves arrives at such an extent, that the features of the tides are materially changed. We have no longer regularly recurring neap and spring tides, but at neap tides the two waves obliterate one another entirely, so that only spring tides are perceptible, or else instead of two tides in the day we have four, two due to the moon, and two to the sun. The former of these cases has an example at Otaheite, in the Pacific, where there is no tide, except at springs, and then near midday. When the time of tide arrives at three in the afternoon the tides vanish, and do not reappear till they would in regular course arrive at about nine o'clock.

At Courtown, on the coast of Ireland, we have an example of the two waves being entirely separated at neaps, for there are then four tides in the day.

These, however, are extreme and exceptional cases, and in each case the rise is very small. The general principle is that both waves are modified, both in their speed of travelling and in their dimensions, by the conformations of the channels in which they travel, but that they are modified in slightly different degrees.

CHAPTER VI.

THE TIDE WAVE IN REALITY.

Impossibility of making tidal observations in the open sea. Tides on the coasts of an island. Of a continent. Effects of coral reefs. Determination of the age of the tide. Stationary and peculiar undulations. Whewell's cotidal map.

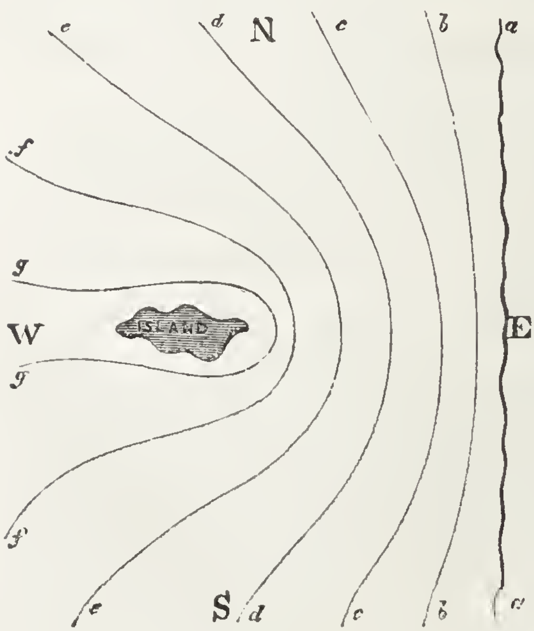
We have explained how utterly impossible it is to say beforehand what are the movements of the tide waves. All our knowledge must depend upon observation, and the more perfect and numerous the observations, the better will be our means of reducing them to some general law.

The making of tidal observations, however, in such a form as shall tend to assist this branch of the inquiry is attended with many difficulties. In the first place, there are no means at our disposal for measuring the rise of tide, or ascertaining the time at which it reaches its height in the open sea. Some fixed point is required to measure from, and the nearest fixed point in mid-ocean is the bottom, which in many parts is five or six miles down. It has been reached occasion-

ally with great difficulty by the sounding line, but we doubt whether it would be possible to appreciate the difference of depth at high water and low water, even if it were a thousand times greater than it probably is.

It is then hopeless to ascertain by experiment what an open sea tide is, or to trace its progress in the deep parts of the ocean. Our observations are necessarily confined to the shores of islands and continents.

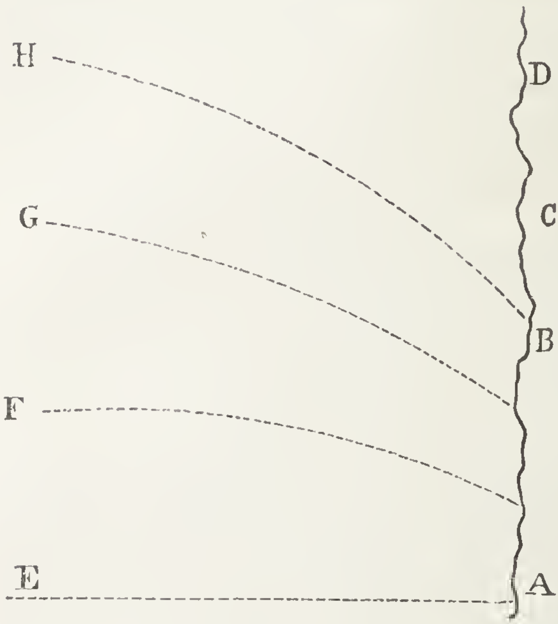
Now an island, or a group of islands, is probably only the summit of what we may term a submarine continent, on which rests a depth of water very much less than exists in the more open parts of the ocean. While then the main body of the wave is travelling on in deep water at a great speed, that portion which is approaching the islands is checked, on account of the diminished depth, long before it becomes visible on any shore, and will not be observed until the main body in deep water has passed. If a wave be travelling from



east to west in the accompanying figure, its summit will take successively the forms of the lines *aa*, *bb*, *cc*, &c., as it approaches the island, the centre part being retarded in going over the shallow water. It may thus be high water at W before the summit of the tide wave arrives at the island ; so that the time of high water on the shores of the island is by no means the same as it is in the ocean due north and south, but at some point considerably farther west. The direction in which the wave travels will also be affected. At any point it will appear to be at right angles with the line of its summit, and thus may be to the north, or to the south, or even on the western side of the island to the east, quite contrary to its original direction. Thus the observations of the tide at the island would give a result very different from that which an observation in mid-ocean would give, if such were possible.

Again, if we have the shore of a continent lying parallel with the direction of the wave's motion, we might at first sight suppose that the regular progression of the time of high water from one place to another would clearly mark the wave's progress. But here again we are liable to be misled.

Let ABCD be a line of shore. Suppose EA to be the line of the summit of the wave at the time it reaches A. Now as the depth of water



is naturally much greater at E than along the shore between A and B, the wave will move from E to F, G, and H, while it is travelling along shore from A to B. The summit of the wave having taken the form H B, will fall upon the shore obliquely, so that the apparent speed between B and D will be much greater than that between A and B; and if there happen to be more than ordinarily shallow water opposite C, it may be high water at D even sooner than at C, and thus give the appearance of a retrograde motion.

Such discrepancies as these then may occur in shore tides, although the motion of the main wave in the open ocean be perfectly regular. If we were sufficiently conversant with the local circumstances of each station of observation, we might select those which seem to present the fewest impediments to the free movement of the wave; but as we can judge of these impediments in so very imperfect a manner, we can only take the average of what appear to be the most con-

sistent results of a number of observations. We know indeed in what proportion the velocity of the wave is modified by the changes in the depths, so that if we knew the depths, we might make a much nearer approximation to determining the real movement of the wave by allowing for the retardation; but it is only of late years that deep sea soundings have been attempted, and we were generally ignorant whether the sea was 1000 or 6000 fathoms deep, and consequently at what rate the tide wave was travelling over it. Indeed we believe the first notion of the depth of the Atlantic was obtained from a general knowledge of the speed of the tide wave. It was known that the tide wave travels up the Atlantic from south to north at the average rate of about 700 miles per hour, and it was thence inferred that the depth was about five or six miles. Subsequent soundings have verified this.

The movement of the tide wave at points within the power of our observation is still farther interfered with, especially in the Pacific and Indian Oceans, by the extensive coral reefs which form barriers round groups of islands, and admit the entrance of the tide wave only at certain points. Thus, when it arrives at the post of observation on shore, it has been retarded, and its direction entirely changed, so that it offers no

evidence whatever of the movements of the tides outside.

The retardations and impediments through which alone we see the tide wave cause variations to the amount of several hours. If they extend to 12 hours, it becomes a question whether the tide which we see is due to one transit of the moon or another. It may be either a very quick, comparatively unimpeded tide formed by a late passage, or a very much retarded tide formed by an earlier one. If we can trace the impediments, we can at once decide; but if not, we must have recourse to another method, which is to compare the heights of several successive tides with the changing relative positions of the heavenly bodies. We know what variations in the tides the changes in the positions of the heavenly bodies will cause, and we have to see how long after such changes of position the variations in the tides actually occur. This interval is called the "age of the tide," and it simply represents the time which has elapsed since the sun and moon were in the position to form it, and includes both the time occupied in forming and the time during which it has since been rolling about upon the sea.

Thus the tide on the west coast of Ireland is two days old; that on the east coast of England two and a half days, and the highest spring tides

occur respectively two and two and a half days after the new and full moon.

From what has been said it will be apparent that even with many and good observations, the tracing of the tide wave's movements is no easy task, and the difficulty is enhanced by the fact that, although the general movement of the tide wave is that of a progressively advancing undulation, yet in many cases it assumes other forms, which can only be recognized and distinguished from the progressive wave by very numerous and detailed observations. One of these forms is that of a stationary undulation, a mere rising and falling of the water simultaneously over a certain length of coast. In other cases the time of high water differs several hours within a few miles, indicating a slow movement of the summit of the wave from one point to another, guided by some law of fluid undulation different from those which determine the speed of a simply travelling wave. Where such forms of tidal movement as these are, or may be supposed to be, present, nothing but very perfect observation or more perfect theory can help us to a satisfactory conclusion.

All these considerations make it necessary for us to be very cautious in drawing any conclusion as to the course of the tide wave upon the surface of the globe, as the evidence at our command may so easily mislead us. There are, how-

ever, certain general principles which appear to be pretty clearly established, and according to these we shall in the succeeding chapters endeavour to follow the course of the wave, pointing out as we go those features which appear to claim especial notice.

We should not do justice to our subject were we to omit mention of the labours of Dr. Whewell in this field. In 1833 he presented to the Royal Society an essay entitled "A first Approximation towards drawing a Map of cotidal Lines." In a map which accompanied this paper, he laid down lines through those points on the earth's surface at which high water occurred at the same time. Thus in the Atlantic, for instance, he found a place on the coast of Africa, and another on the coast of America, where it is high water at four o'clock by Greenwich time; then two other points where it is high water at five o'clock, and so on. These lines he denominated "cotidal lines," and they were intended to represent the position of the summit of the travelling wave at any given hour. It will be readily understood that if a number of these lines could be laid down with accuracy upon a map, they would exactly represent the movement of the tide wave from hour to hour.

We have shown, however, how impossible it is to obtain the information necessary for fixing the

position of the lines at sea; that shore tides and island tides give at the best only an approximation, and often entirely mislead; and farther, it is evident that cotidal lines will not represent at all a stationary undulation. On this account then, while we have made full use of Dr. Whewell's labours, and adopted in great measure his views, we have thought that the mode of illustration of which he made use in a very early period of his researches is not the most correct, although it is undoubtedly the most graphic; and we feel the more justified in this opinion, as Dr. Whewell himself pointed out the imperfection of this mode of illustration in some of his later papers on the subject. These few words of explanation, however, seemed desirable, as Whewell's cotidal map has sometimes been considered more of an authority than the author of it can ever have intended.

CHAPTER VII.

TIDES OF THE PACIFIC OCEAN.

West coast of America. High water earliest under the equator. Diurnal inequality. Progress across the ocean. New Zealand. Islands of east coast of Asia. Australia. Cases of apparent single day tides. Tides of the China Sea. Tonquin. Singapore. Sourabaya. Cause of the diurnal inequality, and its varieties.

Seeing what a complete barrier the continent of America forms between the Atlantic and Pacific Oceans, we can scarcely imagine that the tide which is raised in the Pacific, after the passage of the moon over the western coast of South America, can have travelled from any other part of the globe, or can be otherwise than directly due, in great measure at least, to actual attraction; whether we consider that attraction to manifest itself in the form of a wave of the first order, or in any other way that our fancy for one hypothesis more than another may dictate. Now what do we find in reality?

We find, first, that the part of the coast on

which the tide is earliest is that immediately under the equator, and that it becomes successively later as we travel north or south. The southern branch shows a regular progress; the northern is also regular, with the exception of some peculiar form of local undulation on the coast of Mexico, which seems to throw the wave back some hours between Acapulco and St. Blos. Secondly, we find that in most of the observations there is recorded a remarkable inequality of the two tides of the same day; the tide in the northern hemisphere being very much smaller when the moon is acting at her extreme south declination, and that in the southern hemisphere is smaller when the moon is in the north. We find in the charts of the American coast survey, made for the United States government in 1852, the following note, which applies in a general way to the west coast of North America:—"1. The tides consist generally of a large and small tide on the same day, so that of two successive high waters in the 24 hours, one is much higher than the other, and of two successive low waters one is much lower than the other. 2. The difference in height varies with the moon's declination. When the declination is nothing, the difference is little, or very small; when the declination is greatest, the difference is greatest. When the declination is nearly nothing, the interval between

the two high waters, or two low waters, is nearly 12 hours, and differs most from this when the declination is greatest."

It is farther stated, that at San Francisco there is a difference of 2 hours in the time of high water, according as the moon is at her greatest declination north or south; that is to say, according as the tide starts, as it were, from the peninsula of California in North America, or from Coquimbo in South America.

The difference of level between the two successive tides is sometimes 2 feet 11 inches at high water, and 3 feet 6 inches at low water.

The tides along the coast of South America have been less carefully observed, but in the neighbourhood of Cape Horn the same feature was observed by Sir J. C. Ross.

Now when we examine the tides near the equator we find a change. At Panama, where there is a rise of 15 feet, there is no apparent diurnal inequality. At Guayaquil there is "apparently a diurnal inequality in high water heights," but it cannot be very marked, as the total range from high to low water is 10 feet, so that no very great nicety of observation would be necessary to make it certain, if it were considerable in proportion to the total range. In other parts near the equator it seems much less marked than farther north and farther south. The reason

is evident; these places are nearly equidistant from the two starting-points north and south.

The height to which the tide rises on this coast is different in different places. In the bays, as Panama, it reaches 12 or 15 feet, but at the promontories it is not more than from 4 to 6 feet.

At the Gallipagos Islands, which lie immediately under the equator some 600 miles from the coast, the tide is high 2 to 3 hours after the passage of the moon, and rather before it is high water on the nearest point of the continent. This we might have naturally expected; for, inasmuch as the tide follows the moon, it is clear that the first effect, close to the continent, must be the drawing away of the water from the land, in order to form a tide wave to the westward. A certain space of water behind the moon is required to form a wave; this wave, then, when brought to a head, as it were, we may easily suppose falls back upon the coast, passing the Gallipagos on its way, and then spreads itself north and south, forming high water at all parts as its summit successively washes them. It accomplishes its journey from the Gallipagos Islands southwards to the Straits of Magellan in about 10 hours, and northwards to the coast of Russian America in about 14 hours.

Following the course of the sun and moon

across the Pacific, we pass a multitude of small islands. The tide has been observed on some of these. Its principal characteristics are, a very small rise, often not more than 2 or 3 feet, and great irregularity in the times.

The only approach to a *law* which seems to hold in the observations collected by Dr. Whewell is, that at one-third of the whole number of points of observation, high water takes place at between 6 and 7 hours after the passage of the moon, so that there are more high waters at that interval after the moon than at any other. It is at 6 hours after the moon's transit that the summit of the wave first touches New Zealand, the easternmost of that congregation of islands which would seem to form a barrier to the direct progress of the wave. On the coast of New Zealand it divides and travels north and south, reaching the northernmost point of the island at 8 hours, and Dusky Bay, the southernmost, at 11 hours after the moon's transit[1].

At the Feejee Islands, the New Hebrides, and

[1] This is Dr. Whewell's view (Phil. Trans. 1833, 1848). The Admiralty surveyor's observations made within the last few years confirm it so far as regards the northern branch, but on the east coast of the southern island is a local undulatory movement, which quite changes the time of the tide there. Dr. Whewell's hypothesis, however, refers to the movement of the great ocean wave, and although not *confirmed*, is not necessarily *refuted* by these observations.

New Caledonia, which lie nearly due north, the time appears to be also about the same, 6 to 7 hours after the moon; but in approaching the eastern coast of Australia and New Guinea, it is a little retarded, being there 8 hours after the moon.

At the Bonin and Loochoo Islands, north of the equator, the time is also about the same, but it is retarded considerably before reaching the coast of China.

In almost all the tides observed in the Pacific there is more or less diurnal inequality, both in height and time, and a want of due attention to this fact may in some cases have introduced confusion into the records of the observations. It so happens that the diurnal inequality on our own coasts is so small, that it is considered a comparatively unimportant matter; our navigators in distant seas are often unprepared for such a phenomenon, and facts, which are really of great importance to be observed, have sometimes been set down as merely accidental irregularities due to local causes. This may account for many apparent anomalies.

On the whole, with regard to the tides of the Pacific, we cannot but be struck with their great similarity to what we should be led to expect them to be from our knowledge of their primary causes; and considering our ignorance of the effect of the

resistance to the first formation of a wave, and of the impediments to its movements after it has been fairly formed, we think we may rest satisfied in the belief that the Pacific tides are the nearest approach to the primary tide wave which we can find on the face of the waters.

During its passage across the Pacific, the undulatory movement which it communicates to the water must be transmitted north and south in various branch waves. The northern ones would meet the great North American branch at various points, and may probably modify its movements to a greater or less extent. The southern branches are lost to our view in the great expanse of the Southern Ocean. They have not been traced, as the land which lies in the neighbourhood of the South Pole is little known; but we find in the South Atlantic a great wave, a day old, travelling northwards.

This we may reasonably suppose has been formed by the lost undulation of the Southern Pacific, which having rolled past the southernmost regions of the Antarctic Ocean, is now coming up on the opposite side of the earth.

Here we shall leave this great wave for the present, while we return to the Pacific wave, which we left on the eastern shores of Australia and New Zealand.

The spring tides rise on the eastern shores of

New Zealand 7 to 8 feet, increasing in the bays and inlets to 10 or 12. On the west side the range is somewhat greater, being in Nelson and Massacre Bays, near Cook's Straits, 14 feet. There is a regular diurnal inequality of about half a foot in height, and an hour and a half in time.

Off the north-east coast of Australia, where the tide wave first arrives, there lies an immense coral formation, called the Great Barrier Reef. It is from 50 to 100 miles from the shore, and though outside it there is a depth of 100 to 200 fathoms, within it the depth is no where more than 20, and generally not more than 10 fathoms.

Any observations made within this reef on the main shore can evidently give but little idea of the state of the tide outside, as the wave can only enter at certain points, and when within the reef will be much affected in its progress by the reduced and variable depth of water. At the southern extremity of the reef, however (Sandy Cape), it is high water 8 hours after the moon's passage; while at Raine Island, which lies just outside the reef, near its northern extremity, it is also nearly 8 hours after the moon's passage. It is, however, 45 minutes later in actual time, as Raine Island lies about 10 degrees westward of Sandy Cape.

At the Lousiade Archipelago, due north of

Sandy Cape, islands which lie to the east of New Guinea, the time is about the same; but after touching the coast of New Guinea it falls behind the moon, and at the northern side of Torres Strait is an hour later, namely, 9 hours after the moon. The range of tide is 6 feet at the Lousiade Islands and New Guinea, and from that to 10 feet on the Australian shores. The diurnal inequality at Port Bowen, south latitude $22\frac{1}{2}$ degrees, is as much as 3 feet for high water, and 1 foot for low water. We have not met with notices of this feature at other points in this particular region, but no doubt it exists.

The tides of the coasts of Australia have been observed in some detail in every present or possibly future harbour by Admiralty surveyors; but these observations, almost as much as those of the islands of the Pacific, are of exceptional cases, creeks, rivers, and bays, which are very different from the great main wave of which we are now speaking; and we are not aware that any observations have been made, or indeed could be made, to verify the hypothesis that a great wave passes to the westward, round the south-west extremity of Australia, into the Indian Ocean. Still we can scarcely refuse our assent to the hypothesis, as it appears almost a self-evident one, at any rate until one more probable is presented. The coast between Sandy Cape and

Bass's Straits receives the tide between 8 and 9 hours after the moon's passage, being generally later to the southward. The height varies from 4 to 9 feet, and the diurnal inequality is considerable. The wave seems to pass through Bass's Straits, with less deviation than is often met with in localities of similar conformation. The time is later than at the entrance, but within the straits varies from half-past eleven to one o'clock on the days of new and full moon, the average range of spring tides being 8 or 9 feet. At Adelaide it is high water at half-past three, about 3 hours later than in Bass's Straits; and here the diurnal inequality is very large, and the amount of inequality appears to change very regularly two days after the moon. The inequality, when greatest, is as much as 4 feet; 3 feet for high water, and 1 foot for low water. The time of the two tides also varies considerably.

At King George's Sound, near the south-west point of Australia, the diurnal inequality of the times is so great, that sometimes the two tides come so close together, and the water falls so little between them, that there appears to be only one tide in the day. The range however is very small, 1 to 4 feet.

After passing the south-west point, the two tides, which at King George's Sound had come so near together, again separate, that is, the diurnal inequality becomes less. The tide, however, is

still very small. At the Houtman's Albrolhos Islands, in latitude 29°, the inequality is $1\frac{1}{2}$ foot at high water, and $\frac{1}{2}$ foot at low water; in time, 5 hours at high water, 2 hours at low water. This is in a rise which averages only $2\frac{1}{2}$ feet.

From here the tide increases in range, and decreases in the amount of diurnal inequality. At Depuch Island, in latitude $20\frac{1}{2}$° S., the tides recur nearly at the regular intervals of 12 hours and some minutes, but there is a difference of 2 feet in the height of consecutive tides. The whole range is $14\frac{1}{2}$ feet.

We may here remark, that while in going northward the diurnal inequality of time diminishes, and at last vanishes, and the inequality in height continues, in going westward the reverse takes place. At Kerguelan's Island, in latitude 49° S., longitude 70° E., the two tides of the day are the same height, but there is an inequality of time of 1 or 2 hours.

Returning to the coast of Australia, the tides in going northward continue to increase. At about latitude 15° south, they rise 20 to 30 feet, and even upwards of 37 feet in the bays which lie along the coast there. We have no information of the diurnal inequality. The time of high water is twelve o'clock at new and full moon, so that the wave has been about 13 hours in coming from Bass's Straits, supposing it to have followed the coast of Australia, or 18 hours from the Pacific.

From here again the range of tide diminishes, and the diurnal inequality we again find to be large. At Port Essington, in Victoria Peninsula, there is a diurnal inequality of 4 feet at low water, and also an inequality, though less regular, at high water.

In the Gulf of Carpentaria the inequalities are again so great, as to have led Captain Flinders, the earliest navigator in those regions, to believe there was only one tide in the day. Whether this be due to the great inequality of time bringing the two tides together, or to the great inequality of height causing the smaller one to be overlooked, there are not sufficient observations recorded to enable us to determine.

Another branch of the Pacific tide wave enters the China Sea, and then presents very remarkable features.

Off the east side of the Island of Formosa it is high water at ten o'clock, at new and full moon, and the rise is about 6 feet. Between the island and the main land the tide rises to the height of 18 or 20 feet, and high water takes place about 2 hours later. In passing along the coast of China, however, the height is reduced again to 8 or 9 feet, but in the Gulf of Tongquin it again attains a height of 18 to 20 feet at some times, at others it is 2 to 4 feet only. There is apparently only one tide in the 24 hours, and its rise is

greatest when the moon's declination is greatest. When the declination is north the tide flows when she is above the earth, and when it is south when she is under the horizon. When she is near the equator the tide becomes very small[2].

At Singapore, the southern part of the Peninsula of Malacca, the tides present somewhat similar features, and the observations having been made and examined with great care, it has been found that there are really two tides in the day, but the diurnal inequality is so large, being sometimes for low water as much as 6 feet, while the total average rise at spring tides is only 7 feet, that the second tide is scarcely observable. It was found that the changes followed the moon at an interval of a day and a half[3].

It is curious to observe how we have now passed from the direct influence of the moon. Singapore lies within a degree and a half of the equator, so that if the tide were one directly due to the moon the two waves would be exactly alike, its position being half-way between the latitudes, where the two are respectively formed; whereas it is a very remarkable instance of inequality of the two waves. Other parts of the China Sea, there can be little doubt, present similar peculiarities in

[2] Horsburgh's India Directory.

[3] Philosophical Transactions. Whewell, 1837.

their tides, but we do not possess observations of sufficient minuteness to enable us to decide upon more than the most obvious features.

The same may be said of the tides in the various channels between the islands of the Asiatic Archipelago. There are several isolated observations on record, showing a general rise of from 6 to 10 feet, but any attempt to trace their progress, or to account for their peculiarities, without far more information would be useless.

A peculiarity, however, which manifests itself at Sourabaya, a port on the north coast of the Island of Java, may be noticed. The port lies upon a strait between Java and the small Island of Madura, so that there are two entrances to it, one on each side of the island. In the eastern entrance there are two high waters every day, but they differ in height. The highest is in the day time, when the sun's declination is north, and in the night when it is south. When the sun is on the equator the tides are equal. The higher of the two unequal tides rises $9\frac{1}{2}$ feet, the lower $6\frac{1}{2}$. When the tides are equal, the rise is 8 feet.

In the western channel, when the sun is in the equator, there are two regular high waters at spring tides, but only one at neaps. At all other times there is only one high water, which is in the day time, when the sun's declination is north, and at night when it is south. When there is only

one tide, springs rise $6\frac{1}{3}$ feet, neaps $5\frac{1}{2}$. At the equinoxes, when there are two spring tides, each rises 4 feet, and the single neap tide 5 feet[4].

This brief sketch of the tides in the seas between the Pacific and Indian Oceans will show how great a variety of forms is assumed by the effects of that periodic action of the sun and moon upon the waters of the globe, which we have so fully described; but various as these forms may be, each follows regularly its original exciting cause, and varies with it. In some cases the tide rises 30 feet, in others 3 feet. High water occurs at every hour of the 12, at some part or other. The two tides of the day differ from one another in all or almost all parts, but in some cases it is in the height of high water, in some in the level of low water; in some in the time at which the summit of the wave arrives; in others in the time at which the hollow of the wave passes; but each passes through its regular series of changes from fortnight to fortnight, from year to year, and from era to era, each change as truly following the influence of the different positions of the heavenly bodies, as the varying notes of a musical instrument follow the touch of the performer.

The diurnal inequality, which is so marked a feature in these tides, arises from the fact that the two waves, formed in different parts of the earth,

[4] Maury's Sailing Directions.

travel by routes differing in length, direction, and conformation. We might easily speculate upon the circumstances which might retard a wave formed in 20° north, so as to make it 2 or 3 hours longer on its journey than the following one formed in 20° south. We might imagine that while one wave would take the southern route to the western coast of Australia, the other would pass wholly or in part by Torres Strait and the northern coast. Knowing how materially waves are altered in their forms and dimensions by the conformations of the channels in which they move, we might easily conceive how one would present at some particular spot quite different features from the other; and how in passing from one point to another not far distant, the waves will be changed, not only each one in itself, but one in a different manner from the other, according as it may have taken a somewhat different course. Again, what modifications may not the meetings or the crossings of two waves present! Where the summit of one comes near the summit of another, we shall have a wave of double height. Where the summit of one coincides with the hollow of another, we shall have both obliterated.

It would be utterly impossible, however, with our present knowledge, to say which of fifty possible conjectures is the true cause of the great variety of tides round the coast of Australia. We

can only say that the circumstances under which the waves are formed, and the routes by which they travel, are quite sufficient to cause the varieties we find. There is a great field for observation, which will accumulate facts, and in time these facts will show us general laws, the knowledge of which will have a practical benefit, to an extent to which we can hardly set bounds. How little must the navigators of old have expected the wonderful results to their art, which the exact examination and collection of astronomical facts has produced, whereby their successors can now every day fix their position upon the trackless ocean with almost as much exactness as they could among the well-known objects on the most familiar shore.

Another step is being now made by observations of the ocean itself, its currents, temperature, and inhabitants—upon the winds, and storms, and atmospheric phenomena. These being combined and arranged with intelligence and scientific skill, have already solved many mysteries of the deep, and converted the mariner's dangers into useful aids.

In our own seas, where the tides are more thoroughly understood, they are made to serve us usefully to an extent which is little thought of on shore. As the knowledge of tides in other parts extends, it will bring corresponding practical advantages with it.

CHAPTER VIII.

TIDES OF THE INDIAN OCEAN.

Different conformations of the Pacific and Indian Oceans. Difficulty of tracing the tides in the latter. The Bay of Bengal. Gulf of Martaban. Chagos and Maldive Islands. Arabian Sea. Gulf of Cambay. Persian Gulf. Red Sea. Cases of great diurnal inequality.

We now pass to the west side of the Island of Sumatra. Here, as at our starting-point in the Pacific, we have the equator passing from the land to an open ocean, and we might reasonably suspect a new origin for the tide wave.

There are, however, great differences between this region and that of the American coast. In the first place, the northern part of the tropical belt lies in great measure upon the continent of Asia, so that the moon, when in north declination, passes over land, and the formation of a tide wave by attraction would be much obstructed. The southern part is more free, but the extent of ocean under the direct influence of the sun and moon is

still much less than in the Pacific. The circumstances, therefore, are not so favourable for the formation of a tide wave by direct attraction.

On the other hand, this sea, by its geographical position, is much more accessible to the tide wave of the Pacific, than the Pacific is to that of the Atlantic ; the southernmost point of Van Diemen's Land being 10 degrees further north than Cape Horn, while there are also passages, though intricate ones, among the islands of the Asiatic Archipelago.

We may expect to find, then, that the tide of the Indian Ocean has rather the character of a wave which has travelled from the Pacific by these various routes, than of the direct wave raised by attraction in its own waters.

We have seen that the direct wave, even in the most advantageous circumstances, is very small, while the derived, or travelling wave, has mounted in certain cases to the height of 15, 20, or even upwards of 30 feet. It is to this latter, then, that we must look as the main source of the tides of the Indian Ocean.

If we suppose the main body of the wave to enter the Indian Ocean from the south-east, we shall find that its features on the eastern shores are very much affected by the channels between the islands of the Archipelago, which at once

permit the exit of branches of the Indian Ocean wave, and the entrance of branches from the waves of the Pacific and China Seas.

The tides, therefore, all along the shores of Western Australia, of Java, Sumatra, Malacca, and Burmah, will necessarily be much affected by the combination of these various branches, and we can scarcely expect to find the means of tracing the main wave by the shore tides.

The tides on the coast of Northern Australia, between the meridians of longitude 120° and 130° we stated to have been high. We have no information of the tides north of this nearer than the south-west coast of Sumatra, where the wave is only 2 to 3 feet high, and it vanishes altogether in the northern part of the Straits of Malacca. At Singapore, the southern extremity of these straits, it has peculiarities, described in the last chapter.

We can now trace some kind of a regular progress for the wave. At the Nicobar Islands it is high water at new and full moon at a quarter past nine, and the tide rises 8 or 9 feet. At the Andaman Islands, due north, the tide is a few minutes later. About the islands of the Merqui Archipelago, off the coast of Tenasserim, and on the main coast itself, the arrival of the wave is somewhat later, being probably retarded by the shallowness of the ocean on approaching the coast.

Its height, however, is increased to 18 or 19 feet, and at the head of the Martaban Gulf it rises as much as 24 feet, the greatest tide being here two days after new or full moon, making the tide 2 days old.

At Cape Negrais, the western extremity of the Gulf of Martaban, the rise is 10 feet, little more than at the Andaman Islands. The time is about an hour later. It takes another hour to get to Cheduba, 200 miles north, where the rise is about the same. The range increases to 12 feet at Chittagong, at the head of the Bay of Bengal. Hence it flows up the various mouths of the Ganges. The tide wave exhibits no regular progress along the eastern shore of Hindostan, and the rise is small.

At the Chagos Islands, lying due south of Hindostan, in latitude 6 degrees south, the tide rises 5 to 6 feet, and it is high water at new and full moon at half-past one, which is nearly five hours later (making allowance for the difference of longitude) than the tide on the coast of Australia.

At the Maldive Islands, lying 10 degrees farther north, the tide exhibits a curious feature. The group of islands (which lie in a line due north and south, extending over a space of 300 miles) is surrounded by a coral reef, which only admits the tide wave to enter freely from the north. Here

the time of high water at new and full moon is half-past nine, and it becomes successively later in going southward, till at the southernmost islands the time is one o'clock. This direction is exactly contrary to the general progress of the tide wave. The range is about 5 feet.

At Cochin, on the opposite shore of Hindostan, the range is only 3 feet. The tide wave from thence travels northward. At Goa the time is eleven hours forty-five minutes, and the range is 5 feet. Beyond this the features strikingly resemble those of the coasts of Malacca and Burmah. The tide becomes later as we go north, and the range increases. At Bombay it rises from 14 to 17 feet, at Surat 21 feet, while at the head of the Gulf of Cambay it rises 30 to 36 feet. Passing on, however, to the mouth of the Indus, the range is again reduced to 9 feet. It will be seen upon the map that the conformations of these two coasts are very similar, the Gulf of Martaban being represented by the Gulf of Cambay. In each case the tide in the gulf becomes very large, while the portions of the waves which pass clear of the gulfs retain their original dimensions.

At Bassadore, near the entrance to the Persian Gulf, spring tides rise 9 feet 6 inches, and neaps 3 feet 6 inches, and here a peculiarity occurs similar to that which we noticed on the western coast of Australia. In the Gulf of Cambay there

is a diurnal inequality of 7 or 8 feet in height, but the two tides arrive at their regular intervals; there is no inequality of time. At Bassadore the two tides are of the same height, but the one arrives proportionally 2 hours earlier than the other.

We may remark here, as we did of the Australian tides, that this difference in the manifestation of the diurnal inequality may easily be accounted for, by supposing the two waves, having been originally formed in different latitudes, to take somewhat different routes. One being perhaps a little more easterly than the other, may find a less obstructed path in the ocean than that which is more directed along the shore; it may thus arrive sooner, and be smaller when it arrives at Bassadore. In its route to the Gulf of Cambay it may meet with circumstances which retard it and increase its dimensions, in an equal degree with those which by a different route have affected the other.

This is mere conjecture, which more perfect knowledge may refute or confirm, but we mention it to show how terrestrial causes may affect differently tides formed on different parts of the earth's surface. The tide is here also two days old.

The tide wave flows up the Persian Gulf, and at the head there is a rise of $7\frac{1}{2}$ feet.

The progress of the wave along the southern coast of Arabia is generally to the westward, but it is stated to be irregular; probably its continuous movement is interfered with by meeting a more direct portion of the wave travelling from the south-east. The general range is from 6 to 8 feet; the time, at new and full moon eight to ten o'clock, and at the Straits of Babelmandel twelve o'clock.

There are but few observations of the tide in the Red Sea, and the range is small. It is probable that there is a peculiar movement of the wave, of the exact nature of which we cannot judge without more observations. The time of high water at Suez appears to be nearly the same as at the Loheia River, a little within the straits. It is scarcely likely that the wave travels over this space in 12 hours, and the small rise and irregular time near Mecca would seem to indicate a movement somewhat similar to that which we find on our own coasts, and which we shall describe in the sequel.

The tide wave appears to fall directly upon the east coast of Africa, making high water generally along the coast at nearly the same time, between one and two o'clock by Greenwich time; except in some cases, where either the wave is retarded by the conformation of the ocean bed, or by some peculiar undulation. The range is pretty large

in the Mozambique Channel and for some distance to the northward, being from 10 to 12 feet.

On the whole, we must repeat that the movements of the tide wave in the Indian Ocean are very doubtful, and any view which we can propose must be entirely hypothetical. That which we have ventured to suggest is useful more as a mode of connecting the facts of the actual rise and fall at various places, than as an absolute deduction from evidence. That evidence, moreover, is very meagre, and it is rendered the more so by the great allowance we are forced to make for the diurnal inequality. When the two tides of the same day follow the moon at intervals varying two or three hours, and when the rise of one tide is perhaps double that of the other, and when, notwithstanding this important feature, we are only told that the range is so much, and the time such an hour, we do not know whether these heights and times refer to the larger or the smaller, to the earlier or later tide; or possibly to the mean of the two tides.

A good series of observations, even if they were only in the places from which we now possess the imperfect information, would throw great light upon the subject. We might then find that the tides are to some extent modified by the direct action of the sun and moon; but with the infor-

mation we have, it would be improper to carry our conjectures farther than we have done, or even to offer those as more than the conjectures most accordant with the few and imperfect facts which have been collected.

CHAPTER IX.

TIDES OF THE ATLANTIC OCEAN.

General course of the main wave as evidenced by the islands and projecting parts of the continents. Tides of South Africa. Neighbourhood of Cape Verde. Coast of Morocco. Spain, Portugal, and France. South America. South of Cape Frio. From Cape Frio to the mouth of the Orinoco. West India Islands. United States. St. Lawrence. Baffin's Bay. Gulf of Mexico. Mediterranean.

WE have before stated that a wave about a day old appears in the South Atlantic, travelling northwards. This tide wave we imagined to have been formed in the Pacific, and taking from thence a southerly direction through the Antarctic Ocean, to have reappeared in accessible latitudes with what has become, since passing the south pole, a northerly motion. This wave we have now to trace.

On the day of new and full moon the passage of this wave makes high water, by Greenwich time, as follows:—

At the Island of Tristan d'Acunha	50 m. past 12
At St. Helena	20 m. „ 3
At Ascension	5 m. „ 6
(Here there appears to be some retardation.)	
At Fernando Norouba, off Cape St. Roque	10 m. past 6
At the Cape Verde Islands .	30 m. „ 7
At Bermuda	30 m. „ 11
At Nova Scotia	15 m. „ 12

The range, so far, is small, varying from 2 to 5 or 6 feet, and in some parts of Nova Scotia, 8 feet.

Bending to the eastward round the Azores it reappears—

On the S.W. coast of Ireland at	4 o'clock
On the N.W. ditto . . .	6 „
At the Hebrides . . .	7 „
At Christiansund, coast of Norway	19 m. past 10
At Vœroe, in the Lofoden Islands	12 o'clock
At the North Cape . . .	2 „

The range on the British coasts is from 10 to 12 feet, on that of Norway 2 to 9 feet.

Beyond the North Cape we have no farther connected information, but it is most probable that the tide wave is propagated through the Arctic Ocean, and it is not impossible that it may even emerge through Behring's Straits into the Sea of Kamskatka, and there combine with the Pacific wave. We know that there are pecu-

liarities in the tides of that region, which might be accounted for by such a combination, but our information is not sufficient to justify us in positively referring them to this cause[1].

In thus tracing the northward course of the Atlantic tide wave, we have not touched on the shores of Africa or South America; we have touched but once on that of North America, and on the continent of Europe only in the north ot Norway. As might be expected, the shore tides present very irregular times. The wave before it reaches the continental coasts is retarded and modified so as to destroy all evidence of its progress. We can, however, compare the times on the coasts with the nearer approximation to the true progress which we obtain by means of the island tides.

At Algoa Bay and the Cape of Good Hope the time is from an hour to an hour and a half later than at Tristan d'Acunha. Along the whole coast from the Cape of Good Hope to Cape Palmas, the tide is apparently rather earlier than at the islands in the same latitudes. The observations are not numerous enough to render this certain, but if it be true, it must be owing either to some local

[1] Peculiarities of the diurnal inequality at Petropauloski, and other places, described by Whewell. Phil. Trans., 1840.

undulation, or possibly to some effect of the direct attraction of the heavenly bodies.

From Sierra Leone to Cape Verde, the times are more in accordance with the motions of the main wave, and the tides are much stronger, being from 8 to 12 feet rise, while on the coast of Guinea they are not more than 6 or 7 feet.

In the space between Cape Blanco and the Strait of Gibraltar, opposite which lie the Canary Islands and the Azores, there appears to be a peculiar local undulation. The tide at Cape Blanco is four hours later than at Cape Verde, while on the coast of Morocco it is little more than an hour later than at Cape Blanco. The times at the Canaries and the Azores are again quite different from those on the coast of the continent. This region, in fact, would appear to lie out of the main route of the wave, and to receive its tides by a kind of secondary undulation. The range of tide, however, is greater than that of the main Atlantic wave in the same latitudes, being from 6 to 10 feet.

Now although, on looking at an ordinary map, we see no reason why the tides of this region should have a movement so different from that of the main ocean, yet we find by soundings made recently [2] that the depth of this part of the ocean

[2] Maury's Sailing Directions and Chart.

is very much less than it is more to the westward. The general depth in the line between Ascension and Bermuda, passing a little to the westward of the Cape de Verde Islands, is from five to six miles, while between the latter group and the Azores the depth is only from two to three miles. Here then we see indicated, though the materials are but scanty, a correspondence in *fact* with the theory, that the speed of the wave is affected by the depth of the ocean.

The tides of the coast of Spain, Portugal, and France, however, would appear to be more directly due to the main wave, which having passed to the northward of the Azores, falls upon them in a nearly easterly direction, thus striking the general line of land obliquely. The range is greater than we have hitherto found it in the Atlantic, being from 10 to 12 feet on the Portuguese, and 19 or 20 feet on the French coast. Of the progress as marked on the west coasts of Ireland, Scotland, and Norway, we have already spoken.

We will now see how this great Atlantic wave manifests its presence on the American shores.

We find the earliest tide at Cape Frio, where the time (four o'clock by Greenwich) agrees pretty well with the times at the islands. The range is here 4 feet. From hence there is a progress

north and south. Taking first the southern branch, we find that it travels along the coast regularly for some distance, with a height little varying, till near the Rio de la Plata it vanishes.

Between this point and Cape Horn the tides are very peculiar. At the Gallegos River, a little to the north of the Straits of Magellan, the range is upwards of 40 feet. North and south of this, the range gradually decreases. The time of high water exhibits no regular progress. Dr. Whewell has suggested that the Atlantic wave approaching from the eastward, converges by very slow degrees upon St. George's Bay, travelling along the coast from south and north to this point. We think, however, that farther observations on the spot, aided by our increased knowledge of the peculiar movements which the tide wave affects, would lead to a more satisfactory explanation than this. The point of greatest range at the Gallegos, and the diminishing range on either side, has its parallels on our own coasts, as we shall have occasion to explain by and by.

At the Falkland Islands there is a diurnal inequality, which at the greatest is to the extent of 2 feet on the level both of high and low water, and its changes follow the corresponding changes of the moon's declination by a day and a half.

This feature is very like that of the Pacific tides. It is very probable that the peculiarities in the tides of this region are in some measure connected with the meeting of the Atlantic wave with that which has travelled down the west coast of South America.

We now return to the branch which runs northward from Cape Frio. It increases in height as it proceeds: from 4 feet at Cape Frio it becomes 6 to 8 feet at Pernambuco, and 8 feet at the Aracati river, near Cape St. Roque. The progress is regularly to the north, and westward as far as Maranham, and somewhat slower than that of the main Atlantic wave. Between Maranham and the mouth of the Amazon there is a break in the regularity of the progress, and beyond the Amazon, at Cayenne, and the mouth of the Orinoco, the time more nearly coincides with that of the main wave. On this latter part of the coast there seems to be a distinct branch from the main wave, which combining with the Brazilian branch near the mouth of the Amazon, may cause some irregularity of the time there. The range at the mouth of the Amazon is 12 feet; at the Orinoco only 6 feet; at the West India Islands the tides are very small and irregular.

The tides on the coast of the United States

have been the subject of valuable observation, but we are not aware whether any definite theory of their movements has been presented.

It will be observed that between Nova Scotia, on the coast of which we imagined the great main wave to impinge, and the Peninsula of Florida, there are two prominent points, Nantucket Island and Cape Hatteras. The times of tide at these two places differ $6\frac{1}{2}$ hours, so that it is high water at one when it is low water at the other. All along the coast between the two, it is high water nearly simultaneously, and at about 2 hours later than at Cape Hatteras, or $4\frac{1}{2}$ hours before Nantucket.

Southward from Cape Hatteras the progress is regular towards the south, five hours being required for the transmission of the tide wave to the Florida Keys.

Between Nantucket and Nova Scotia the time is also nearly simultaneous, being an hour and a half earlier than at Nantucket, and differing $8\frac{1}{2}$ hours from the time on the coast of Nova Scotia. The rise at Nantucket is small, not more than $2\frac{1}{2}$ feet at springs. At Cape Hatteras it is $5\frac{1}{2}$ feet, and in the bay between the two from 6 to 7 feet. South of Cape Hatteras it increases to $8\frac{1}{2}$ feet in the centre of the bay, and thence diminishes to $2\frac{1}{2}$ feet at the southern point of Florida. All these are very moderate ranges. On the coast of

Nova Scotia it is $5\frac{1}{2}$ to 8 feet, which is also a small rise; but between this and Nantucket Island at the entrance of the Bay of Fundy, it is 13 feet. This is itself a considerable increase; but in proceeding up the bay the range still farther increases, till at the head occurs the greatest rise of tide in the world, stated by the best accounts to be 60 feet at spring tides. These North American tides are evidently the scene of some very curious undulatory movements of the surface of the ocean, which have yet to be explained.

The tide wave enters the Gulf of St. Lawrence between Nova Scotia and Newfoundland, and also by the Straits of Belle Isle to the north of Newfoundland. These two waves appear to counteract one another on the west coast of Newfoundland, where there is scarcely any tide.

To the south of Prince Edward's Island we meet with a peculiarity which reminds us of the Pacific, viz. a single day tide. This is caused, however, probably by some curious combination of two waves which obliterate one another, except the diurnal inequality. That is to say, when the high water of the greater tide meets the low water of the smaller tide, there remains a rise equal to the difference of the two. When the high water of the smaller tide meets the low water of the greater, there remains a hollow equal to the difference of the two, making one tide in the day with

a rise equal to the diurnal inequality of high and low water combined.

The tide flows up the St. Lawrence to above Quebec, where there is a range of 20 feet.

The tide wave proceeds up Baffin's Bay. At Holsteinburg, on the coast of Greenland, it is $6\frac{1}{2}$ hours later than at the Strait of Belle Isle, and 10 feet high. At Port Leopold, in Barrow's Straits, it is 7 hours later still, and 6 to 8 feet high.

We have now to return to two branches of the Atlantic tide wave, that of the Gulf of Mexico, and that of the Mediterranean.

We have already stated that among the West India Islands the tide is very small, and the water being much affected by local influences of wind, what little tide there is, is difficult to observe.

In some parts of the Gulf of Mexico, however, it has been carefully observed by the United States Government naval surveyors. At Cedar Keys, on the west coast of Florida, average springs rise 2 feet 10 inches, neaps 1 foot 10 inches; but there is a diurnal inequality sometimes amounting to 4 feet, so that while one tide is 5 feet high, the other will be only 1 foot. In time there is an inequality of 3 hours. The changes of the tides follow the moon's movements regularly, the diurnal inequality vanishing when she is on the

equator. The tides are regular except in storms, which however sometimes quite reverse them, making high water come at the ordinary time of low water. A storm has been known to raise the water 11 feet.

In Mobile Bay, near the mouth of the Mississippi, only one tide in the day is perceptible when the moon is at her greatest declination. There are two small ones when she is in the equator. The same may be said of the whole of the Gulf of Mexico, and the Caribbean Sea, so far as the tides have been examined. Now this diurnal inequality in the small tides of the Gulf of Mexico is as great in amount as the diurnal inequality of the high tides which rise on the coast of England. All other variations of the tides, such as those due to centrifugal force, distance of the heavenly bodies, &c., are nearly, if not quite, proportional to the range of the tide. This important difference would rather incline us to the belief that the tide of the Gulf of Mexico is in great measure due to an independent wave raised by the attraction of its own waters, and not to a propagation from the Atlantic.

The other branch of the Atlantic tide wave to which we alluded is that of the Mediterranean. This sea is generally called tideless, and it is certain that, while there is a wave of 11 feet at Cadiz, it is reduced to $3\frac{1}{2}$ feet at Ceuta, just

inside the Strait of Gibraltar, 3 feet at Malaga, a little farther on, and is soon after lost to ordinary observation. It reappears, however, in the Adriatic, rising 3 to 5 feet at Venice, and also on the coast of Egypt there is said to be a tide of about 18 inches.

CHAPTER X.

TIDES OF THE BRITISH SEAS.

Principles of tidal currents. In an open channel. Tide and half tide. Gulf tides. Tides of the Irish Sea. Currents in the Irish Sea. Bristol Channel. Similarity of the Irish and English Channels. Course of the tide wave in the English Channel. The North Sea. Progress down the east coasts of Scotland and England. Node opposite Yarmouth. Stationary wave of the Straits of Dover. Progressive wave on the continental coast. Currents of the English Channel and North Sea. Revolving currents. Want of diurnal inequality in the Thames. Double tides.

We now come to a locality which is especially favourable for promoting our knowledge of the science of the tides; first, from its being the scene of a great multitude of careful observations; and secondly, from the tides being generally of very large dimensions, so that the phenomena are, as it were, impressed in very large and plain characters.

If the British Isles were situated at a greater distance from the continent of Europe, and from each other, and if the Irish Sea, the English

Channel, and the North Sea were as deep as the open Atlantic Ocean, the ocean tide wave would wash the east and west shores simultaneously, and we should have a regularly progressive wave from south to north on both sides at once.

This, however, is so far from being the case, that the North Sea receives the whole of its tides from the northwards, even as far as the Straits of Dover; and in the Irish Sea, the wave which enters by St. George's Channel meets another branch from the north before it can escape. We have, therefore, in two cases the means of examining the phenomena of meeting waves; and the results which we shall find here will show us, that farther investigation of apparently anomalous facts in less known localities may render the latter equally consistent with the general laws of the tides.

Before proceeding to the particulars of the tidal movements of these seas, we must explain some points in connexion with the nature of waves, which are necessary for the comprehension of these movements.

Hitherto we have only spoken of the motion of the wave or undulation. The motion of the water of which the wave consists has not been considered. Indeed, in an ocean of many thousand feet in depth, this motion must be insigni-

ficant. A very slow current of a great quantity of water is sufficient to supply the wave. But when we come into a shallow sea, the movement of the water becomes of importance.

Suppose that a wave 20 feet high has to pass through a channel 120 miles long in 6 hours. The quantity of water in the channel will be increased for that time by the bulk or volume of the wave. In order to supply this additional quantity of water, the whole depth is put in motion by the fundamental law of the wave of the first order. The quantity of water in the wave, then, remaining the same, the less the depth, the quicker must be the current to supply it. If the depth be 200 feet, the current must average about one mile per hour, if 400 feet, half a mile per hour, or if 2000 feet, one-tenth of a mile.

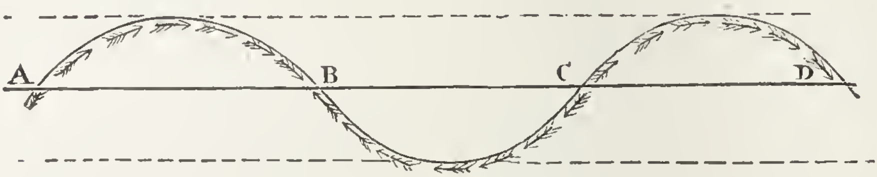
On the other hand, however, the bulk of the wave increases with the depth, because its speed and length increase, so that the quantity of water required is increased. The ratio of increase, however, from this cause is less than the ratio of decrease of speed.

It is unnecessary to pursue this subject into much detail; the general principle is a simple one, viz. that in a deep sea we have a quick movement of the wave, and a slow movement of the water; in a shallow sea a slow movement of

the wave, and a quick movement of the water. In shallow seas, then, another element becomes of importance, namely, *tidal currents.*

If a tide wave have to pass through a channel open at both ends, so that it goes in at one end and out at the other, the current of the water must go with it; but although the wave never returns, the water must do so; there must be an equal current in the opposite direction, otherwise the whole of the water would in course of time be carried from one end of the channel to the other. The passage of the tide wave then produces two currents; one in the same direction as itself, the other a compensating current in the opposite direction. These are sometimes called "flood and ebb" currents; but the term, although sanctioned by usage, is not a correct one, because the terms flood and ebb are applied to the rising and falling of the water, which is quite a different thing. The use of the flood current is to supply water for the wave, and the wave requires water after its summit has passed any particular point, so that at that point *flood current* continues, though *ebb tide* may have commenced. Although therefore, at first sight, we might be inclined to imagine that the current will run one way while the tide is rising, and the other way while the tide is falling, we shall see by a little consideration

of the connexion between the current and the tide wave, that in the case of a travelling wave the rule will be this:—While the sea is *above* half tide level, the water runs *with the wave*, while it is *below* half tide level, the water runs *against the wave*.



Suppose the above figure to represent the surface of two waves, and the arrows to represent the direction in which the streams are running; separating at A and C, meeting at B and D. In such a case the water at A and C must fall, that at B and D must rise. One side of the wave rising while the other is falling, necessarily makes a travelling wave.

This is the most ordinary relation of the tidal streams to the tidal wave, and it is technically called "tide and half tide."

A great portion of the tides on the British coast, however, are in a state exceptional to this ordinary law, and we now proceed to explain the principle to which we shall have to refer them.

Suppose the tide wave to enter a gulf, instead

of a channel with an opening at the other end to allow it to pass out.

At the entrance of the gulf the wave will travel as in an open channel, and the current will change its direction at half tide. At and near the head of the gulf, however, it is clear that so long as the water is running up, there being no escape for it, the tide must rise, and directly the current turns, the tide will begin to fall, owing to water being taken away from it. As we proceed up the gulf, then, we shall find the change of current become nearer and nearer to high water, till at the head the change of current and the change of tide are simultaneous.

The same effect will be produced if, instead of a closed head to the gulf, the tide be met by a counter tide, which is coming in the opposite direction. The current will be stopped, not by a solid obstacle, but by a stream of water running against it. While the streams are running towards one another the water must rise, and it will go on rising till they separate, when it will begin to fall.

This meeting of two waves is found both in the Irish and English Channels. We may therefore expect to find the tides in them present the appearance of a stationary rather than a travelling wave, while the great rise of tide, and the comparatively small depth of the seas make the currents

a very important feature, on account of the force of momentum which they communicate to a vast body of water.

Such are some of the most obvious circumstances which affect the tides in our own seas, and to a greater or less extent in all inland seas. We now proceed to examine the facts as we find them.

The Atlantic tide wave strikes the Scilly Islands and Cape Clear, the south-west point of Ireland, almost simultaneously. It then travels regularly up the north coast of Cornwall and the south coast of Ireland for an hour, till it arrives on the latter coast, at the entrance to Waterford Harbour (Dunmore Head). About the same time it falls upon the south-west point of Pembrokeshire. As far as Dunmore Head the tide wave has been gradually increasing in height from 9 or 10 feet, at Cape Clear, up to 13 feet. At St. David's, in Pembrokeshire, it has attained 16 feet. From Dunmore Head it gradually diminishes, until at Courtown, near Arklow, it almost vanishes. Indeed it is probable that both the lunar and solar wave do actually vanish, but not exactly at the same spot, so that there is always a little tide due to one or the other, the recurrence of high water being irregular. From Courtown the wave again begins to increase as we go northward, till at Dundalk Bay it has attained a range of 18 feet.

From the point at which the tide northward of Courtown becomes regular, up to Dundalk Bay, the time of high water is almost simultaneous, and that time is the hour of low water at Dunmore Head, the point at which the tide wave reached its greatest height on the south coast.

Now let us turn to the north coast of Ireland. The tide is nearly simultaneous here and on the south coast; the north-west shore of Donegal corresponding in time with Dunmore, and the range being nearly the same, about 12 feet. From thence it gradually diminishes, till off Rathlin Island it is again nearly extinguished, and only appears in very anomalous undulations, there being, within a few miles, differences of 6 or 7 hours in the time of high water. After entering the narrow straits between Scotland and Ireland, the wave again gradually increases; the time becomes nearly uniform all along the coast, and that time is the time of high water in Dundalk Bay. This northern branch, however, is less regular than the southern, owing to the great irregularities in the line of the Scottish coast. Here then we have along the east coast of Ireland an almost simultaneous rise of tide from Rathlin Island on the north, to Courtown on the south; the wave forming an apex in the centre at Dundalk Bay. The time at the apex is apparently

somewhat later than at the extremities, which have been termed the "nodes" of the wave, but there can scarcely be said to be a progressive motion. On the opposite shore of Wales we find a regular progress from St. David's Head round Carnarvon Bay, and also in the more direct line from St. David's Head by the extreme point of Carnarvonshire to Holyhead, in 4 hours, the time at Holyhead being about an hour earlier than that in Dundalk Bay. Thence, along the whole of the Welsh coast, the coasts of Lancashire and Cumberland, and the south coast of Scotland, as well as at the Isle of Man, the time of tide is very nearly uniform, and the range regularly increases according to the distance from Courtown on the south, or Rathlin Island on the north. Thus along the whole of the Welsh coast, between St. David's and Holyhead, the range varies from 16 to 18 feet. From Holyhead to Liverpool it increases from 18 to 30 feet. Along the English coast, north of Liverpool, it is from 28 to 30 feet, and from the Solway Firth to the Mull of Galloway it again decreases till it is 16 feet at the latter point, and it farther diminishes in passing northwards through the straits. On the Scottish coast no regular progression of time can be traced, as upon the corresponding portion of the Welsh coast, the time being generally uniform with that

of the apex of the wave; but whether this be due to any different law by which the wave is guided, or merely to the anomalies inseparable from so indented a coast, we cannot say.

The tide wave of the Irish Sea then may be simply described as a great undulation between two points, Courtown and Rathlin Island. Twice every day, about an hour before the moon passes the meridian, above or below the earth, the whole of the Irish Sea is at its height. About an hour before she touches the horizon, in rising or setting, it is at its greatest depression. The quantity of water thus passing in and out at every tide is enormous. It is greater in amount than that discharged by all the rivers of Great Britain and Ireland in a year; and the whole of this has to be supplied twice a day by the two channels, north and south. We find then streams running constantly in one direction or the other. That from the south flows up St. George's Channel to a rate, in some parts, equal to 4 miles an hour, impinges upon the Isle of Man, and turns away at the eastward towards Liverpool. The northern one flows between Donaghadee and Portpatrick, attains about the same velocity in the narrow part of the channel, impinges upon the north coast of the Isle of Man, and turns to the eastward parallel to the southern stream. Between the Isle of Man

and Dundalk the meeting of the two streams causes still water, and here the tide rises and falls some 18 feet, without any stream whatever. These streams, throughout the whole extent of the Irish Sea, change their direction at the time that it is high and low water at Liverpool, flowing in during the rising tide, and out during the falling tide.

The Irish Sea tide is only one branch of the great wave which comes in between Cape Clear and Scilly. A branch of almost equal importance is cut off from it by Pembrokeshire, and flows up the Bristol Channel, and this manifests another law of a different kind from that which governs the wave which proceeds up the St. George's Channel. The progress is regular; the time occupied in passing from St. Gowan's Head, the south point of Pembrokeshire, to the mouth of the Avon, being about an hour and a half.

At St. Gowan's Head the rise is 24 feet; at Padstow, in Cornwall, which lies nearly due south, it is 22 feet. At Lundy Island, a little up the Channel, it has increased to 27 feet. At Worm's Head, in Carmarthenshire, it is 28 feet; in Swansea Bay, 30 feet; Nash Point, 33 feet; Minehead and Bridgwater Bay, 35 feet; Cardiff, 38 feet; and Portishead, 44 feet. These are ordinary spring tides. They often rise 3 or 4 feet higher. Popular

report has given to the river Wye, at Chepstow, an enormous range, 60 or 70 feet being talked of in the neighbourhood as an ordinary rise, but this is not true; the rise at the mouth of the Wye is rather less than at the mouth of the Avon, at Chepstow less still. This extraordinary rise in the Bristol Channel is generally supposed to be caused by the gradually contracting shores of the gulf, and to this no doubt it is in part due.

It is very probable, however, that there are other causes connected with peculiar movements similar to those of the Irish Sea, which assist it. Perhaps in the Bristol Channel, as in the Irish Sea, there is a law by which the range increases in proportion to the distance from the node at Courtown, and the rate of this increase is augmented by the converging form of the gulf.

The currents at the lower part of the channel are much influenced by those which enter the Irish Sea, but above the reach of this influence the streams run up and down channel with a considerable velocity, increasing in the higher parts, where the range of tide and consequent proportional quantity of water required to supply the tide increases. The velocity off Lundy Island, where the rise is about 27 feet, is 3 miles an hour at springs. At King Road, where the range is 44 feet, the stream runs $3\frac{1}{2}$ to 4 miles an hour, and at the Aust Passage it rushes through

a narrow part of the channel at the rate of 6 to 7 miles an hour.

In all parts it changes its direction soon after high and low water, as it universally does near the head of a gulf; and in a gulf gradually narrowing, like the Bristol Channel, for a much greater distance from the head than if the sides were parallel.

A rather curious parallelism may be observed in the conformation of the Irish and English Channels. The accompanying sketch[1] represents the two upon the same scale. It will be seen that they are about the same length and average breadth, and that the points indicated by the

[1] From Beardmore's Hydraulics. Second Edition.

corresponding letters in each have a very great analogy to one another. Thus Cape Clear in the Irish Channel (A) is well represented by the land's end (A) in the English. The land's end in the Irish (B) by Abervrach Head (B) in the English. Carnsore Point (C) by Portland (C). The Bristol Channel (D E) by the Bay of St. Malo (D E). And the northern channel between Scotland and Ireland (F) by the Straits of Dover (F).

Now let us see if the peculiarities of the tides correspond in any way. We found the tides progressing in time and increasing in height from Cape Clear to Dunmore a little west of C, and then the progress becoming irregular, and the height diminishing towards the node at Courtown a little to the northward of C. On the English coast we have also a regular progress up to near Portland. The increase of range is not observable, but the diminution from a little west of Portland is very marked, till somewhere in the neighbourhood of Swanage, which in position nearly coincides with Courtown, there is clearly a node. The range is small, the times not in the order of any regular progression; and there are, as at Courtown, at times 4 tides in the day. Beyond this we have, as in the Irish Sea, the phenomenon of a nearly simultaneous tide all the way to Dover, which is the point corresponding to Donaghadee on the Irish coast. On the French coast we have first

a very great range of tide in the Bay of St. Malo, nearly equal in height with the tides of the Bristol Channel, and nearly simultaneous with them. We have a progress from Cape la Hogue by Barfleur and the coast of Normandy to Havre, very similar to that along the western coast of Wales to Holyhead; except that in this case the height increases as the wave progresses, being at Cape la Hogue and Barfleur about 17 feet, but at Havre 22 to 23. There is no enlargement of the channel above Havre similar to that in the Irish Sea, but the channel continues to contract pretty uniformly to the Straits of Dover, and here we find a marked difference in the features of the tide in the two places.

In order to appreciate this, however, we must first follow the wave which passes round the north of Scotland, and by the east coast of England.

The great Atlantic wave reaches the Orkneys and Shetlands about 2½ hours after it has touched the western islands. It appears to pass round the Shetlands, and thence travels regularly southwards. A little later it washes the coast of Norway at Tananger, and there divides; one branch proceeding northwards, and the other southwards. The northward branch we have already traced. The southward may be traced along the south-west coast of Norway into the Skagar-rack. Its height is very small, the greatest range being scarcely more than one foot. On

the coast of Jutland it is imperceptible. The other extremity of the wave, however, on the coast of Scotland, increases as it progresses. The tides near the Pentland Frith are influenced by the combination of the two branches, viz., the impeded one along the north coast of Scotland, and the freer one, which has passed round the Shetlands. On the north-east coast of Aberdeen, however, there begins a regular progress, the time being about twelve at new and full moon, 2 to 3 hours later than at the Shetlands, and the range is from 10 to 13 feet. At the entrance of the Frith of Forth the time is a little after two, the range 14 to 15 feet. At the north of the Tyne it is nearly an hour later. At Scarborough a little after four is the time of high water, and the range is 18 feet. This is 12 hours after the first approach of the wave to the south coast of Ireland.

At the entrance to the Humber the time is twenty minutes past five, and the range has increased to 23 feet. Here, and along the coast of Lincolnshire, is the apex of the tidal range, corresponding to that which we pointed out at Dunmore Point, on the south coast of Ireland. It is also very nearly 12 hours later, so that two consecutive waves are simultaneous at Dunmore Point and the Lincolnshire coast. From this the progress continues to the north-east shore of

Norfolk; but the range gradually diminishes, till at Happisburgh it is only 11 feet. Not many miles farther on we come to the node near Yarmouth. Here there are also some movements of the tidal wave, which seem to be analogous to those of Courtown and Swanage, the range being small, about 7 feet. The node, however, does not lie on the shore as at Courtown, but the place at which there is little or no rise and fall of tide is in all probability between Yarmouth and the opposite coast of Holland, where the range is also very small, not more than 2 feet, and the time of high water corresponds nearly with that of low water at Yarmouth.

Southward of Yarmouth, after some miles of irregularity, the time of high water becomes stationary, and simultaneous with that at Dover and the upper part of the English Channel. The range also gradually increases from 7 feet at Yarmouth to 12 feet at the mouth of the Thames, 13 feet at the North Foreland, 18 feet at Dover, and 26 feet at Dungeness.

So far the North Sea tide is very similar to those of the Irish Sea and English Channel. We have in all cases the progressive wave nearly up to the node, and thence, after a short interval of apparent irregularity, the stationary wave rising and falling nearly simultaneously on the greater part of the length between the two nodes.

But the seas in which these stationary waves

are found are very different in form. The Irish Sea at the place of meeting is expanded to a width of 130 miles; the English Channel is contracted by the Straits of Dover to 20 miles, from which it suddenly expands into the North Sea. We have no analogy in the Irish Sea to the coasts of the Netherlands, lying north-east of the Straits of Dover, and here we find a movement of the tides to which there is no parallel in the Irish Sea.

On the English coast to the north of the straits we have the stationary undulation, but on the opposite coast from Dunkirk to Katwyk at the mouth of the Rhine, we find a regular progression accompanied by a regular diminution of the range from 18 feet at the straits, to not more than 4 feet at Katwyk. The time occupied from Dunkirk, where the progression seems to begin, to Katwyk is $2\frac{1}{2}$ hours; high water at the latter place being half-past one at new and full moon, that of the stationary wave eleven o'clock.

Beyond Katwyk the progression is irregular, as though it were the neighbourhood of a node; and here we come nearly opposite Yarmouth.

At the Island of Tor Schelling, north of the Zuider Zee, we have the tide 6 hours later, or alternating with that at Katwyk, and a new progress beginning, accompanied by a regularly increasing range, from 4 feet 8 inches at Tor Schelling to 11 feet 4 inches at Helgoland. Beyond

Helgoland the progress continues along the coast of Denmark, but the range diminishes till at the northern part of the peninsula, Jutland, the tides are nearly extinct, although the same northerly movement of what little remains of the wave appears to continue.

From this it will be seen that the tides on the coasts of Holland and Denmark are very complicated in their movements. The extinction of the tide on the coast of Jutland has not yet been satisfactorily accounted for. There seems no analogy whatever between the circumstances at this point and those at the various nodes, except the extinction of the tides.

Dr. Whewell (Phil. Trans. 1837) suggested that the tides in the North Sea were caused by two great revolving waves, each turning upon a centre; one centre he imagined to be on the coast of Jutland, and the other where we have imagined the node to be, off Yarmouth. At these centres there would be no rise of tide. The idea was a very ingenious and plausible one, and to a certain extent does appear to represent the movement of the wave, especially the larger and more northerly one round the Jutland centre. It is not a movement, however, which we should naturally anticipate for a wave, and it would seem better, until farther facts are on record, to refrain from any attempt at explanation of the phenomena.

We have now to describe the course of the currents in the English Channel and North Sea.

From the entrance of the English Channel, between the Land's End and Ushant, up to a line drawn between Portland Island and Cape la Hogue, and in the North Sea as far south as a line between Lincolnshire and the north coast of Holland, the streams turn at half tide; that is, in the natural manner of an advancing wave. Between Portland and Lincolnshire, the streams approach more nearly in their character to those of the Irish Sea. They are running towards the Straits of Dover, while the water is rising at Dover; and in the opposite direction, while it is falling at that place. They meet therefore at high water, and separate at low water, near the Straits of Dover.

But now comes a remarkable distinction between the Channel tides and the Irish Sea tides. In the Irish Sea, to the west of the Isle of Man, there is constantly still water; a rise and fall without any current. In the case of the Straits of Dover, the place of the meeting of the currents is not fixed; but at one time of tide is in one place, at another time in another place, while at the place where an hour after low water was still water, at three hours' flood is in a rapid stream.

Thus, at the beginning of flood the streams

meet between Beachy Head and Dieppe. As the tide rises, the easterly current advances, and the westerly recedes, till at a little before high water the place of still water is between Dover and Cape Grisney. After high water, the stream between Beachy Head and Cape Grisney continues to run to the eastward, and the separation takes place at Beachy Head. Then gradually the current slackens off Beachy Head, and turns to the westward, so that the place of separation travels eastward as the place of meeting had done, till at low water there is still water a little eastward of the Straits of Dover. In mid-channel the line of separation is nearly where the line of meeting was at high water, but the streams near shore have already begun to run for the flood tide. The space over which the points of meeting and separation thus move, has been called by Admiral Beechey, who first described them, "the intermediate tide." It is important to notice, as it produces an apparent "tide and half tide," though the wave is in reality stationary.

We have now to notice the peculiar effect of the junction of the streams of the progressive and stationary waves, which occurs near the nodes.

In these places there is a meeting or separation of two streams, which do not coincide in the times of their changes; and if they vary a little in

direction, they will produce what is called a revolving current. If a stream running north encounter one of equal force running west, the two will combine into one stream running north-west. But if the northerly stream becomes more strong, while the westerly one becomes more weak, the combined streams will tend more and more to the north, till when the westerly stream has entirely ceased there remains nothing but a due north stream. Now the water which formerly was running west turns and commences to run east. The combined or resultant stream will therefore tend to the eastward a little, and as the northerly stream slackens and the easterly stream strengthens, the two will ultimately result in a due east stream. In this manner the direction of the resultant stream has made half a circle during the time that one stream has been running north. During the other half of the tide, while the water is returning, the resultant stream will make the other half of the circle, and thus the whole will be completed in the 12 hours of the tide.

There are such revolving currents in all the cases where the progressive ocean wave changes to the stationary channel wave. The revolving current for the Irish Sea is off the coast of Pembrokeshire. There is one to the westward of the Island of Alderney, in the English Channel; another abreast of the mouth of the Humber in the

North Sea. In these places the current never slackens, but is continually changing its direction. These points are all rather nearer the open sea than the nodes of the wave, but they are all equally a distinguishing feature of the change from one kind of tide to the other.

There is one point connected with the meeting of the two tides near the Straits of Dover, which should be remarked upon; namely, that the two waves are not due to the same passage of the moon, but the one which has passed round Scotland is 12 hours later than the other. The effect of this is, that in that part where the actual rise and fall is compounded of two tides, there is no diurnal inequality, the higher tide being in all cases equalized by meeting the lower one. Thus, while the diurnal inequality makes at Liverpool a difference of 2 feet in the height of morning and evening tides, at London and Dover there is no diurnal inequality. It is curious that the Thames, which from its familiarity to most navigators has been taken as the standard with which the tides in all parts of the world have been compared, is a remarkable exceptional case in this particular.

The phenomena presented by the tides near the nodes are very curious, and have not, so far as we are aware, been yet fully explained. The double tide at Courtown is probably due to the nodes of the solar and lunar wave being in rather different

positions; but we are not aware how far this explanation will hold good for the regular double tides of Swanage Bay, and the occasional ones of Yarmouth.

There are two other ways in which a double tide may be produced. First, where the place is approached by two channels of different length, and by each of which the wave can arrive. One wave comes in, reaches its height, and begins to fall before the other arrives. This is probably the cause of the double tide in Southampton Water, a wave being transmitted on either side the Isle of Wight. Occasionally also there occur double tides in the Thames, which may perhaps be due to the same cause, when the Channel and North Sea tides are unequally affected by some local disturbance, so as to prevent their meeting in the ordinary place.

A second cause is this: it has been found that when a wave of the first order travels a certain distance over a shallow bottom, its summit becomes depressed, until at last it forms a hollow between two summits. This effect may often be witnessed in the case of breakers upon a flat shore, where one swell of the ocean will be divided into two or more waves before falling upon the beach. A wind wave upon approaching the shore assumes many of the features of the wave of the first order: this among others.

CHAPTER XI.

RIVER TIDES.

Different forms of river mouths in tidal and non-tidal seas. Deposits in a non-tidal sea. Deltas. Deposits in a tidal estuary. Entrance of the tide into a river mouth. Depression of low water. Different phases of the tidal wave as it flows up a river. Flood tide shorter than ebb. The bore. Description of the tide in the river Severn.

One may almost know on looking at a map whether the sea into which a river discharges itself be tidal or no. The form of the mouth is essentially different in the two cases.

Compare on the map of France the Rhone and the Loire—rivers of about the same class. In the case of the Rhone, the river before it reaches the sea is divided into two great branches, and these again are subdivided into others. The Loire has but one mouth, and that one of great width and a taper form.

The Rhone is but a type of all the Mediterranean rivers; the Loire is exactly like the Gironde, the Seine, the Thames, the Severn, and the Elbe.

In America we have the Mississippi like the Rhone on a vast scale, the St. Lawrence with a long bill mouth, and the Amazon with two mouths, it is true, but each like the mouth of the Loire, wide and taper. The Indus and Ganges have each several mouths, but they are all of a taper form.

Now a river is great in proportion to the quantity of water it discharges, and the mouths of tidal rivers are so much larger than those of rivers of the same class without tide, because they have to discharge not only the land water, but the tidal water which periodically flows in.

Of all the water that passes under London Bridge upon the ebb of a spring tide, only about one-twelfth is land water, the remainder is entirely tidal water; and consequently the port of London has the benefit of a river 12 times as large as it would be if there were no tide, or even if the tide were stopped by a dam at London Bridge. At Gravesend the proportion of tidal to land water is very much greater, and nearer the mouth it increases still more. Now observe the effect of this. The discharge of water being greater as we descend the river, the channel is necessarily greater to admit of it, and consequently the effect of the tide is to create a taper or funnel mouth. On the other hand, this taper or funnel mouth is just the form which encourages

a greater rise of tide, and thus the quantity of water to pass in and out is again increased, and the funnel is still more enlarged. The two operations assist one another, and we see the effect, in the large widely expanded estuaries into which our tidal rivers discharge themselves.

On the other hand, look at the effect of the fall of a river into a tideless sea. The size of the river increases, it is true, as it descends, because more water drains into it, but the rate of increase is vastly less than in the case of a tidal river, and towards the mouth especially it is slow, so that the river, where it joins the sea, is practically of the same size as at a distance of 20 miles up.

But although the amount of water is nearly the same, the circumstances in other respects are very different. Every river brings down with it a quantity of earthy matter, sand or mud. Even when the water appears perfectly clear there is generally a slight movement of the lighter particles of earth in the bed, and when the river is swollen with rain, every one knows how turbid it becomes. Now it is a law of running water, that the more rapid the stream, the greater the quantity of solid matter which it can carry with it, and the heavier and coarser will be the nature of the earthy particles. Thus a stream of a certain velocity will sweep along pebbles, a less rapid one fine gravel, another sand, and a gentle stream will

hardly hold fine mud in suspension. It will be easily understood that when a stream is checked, either by entering a pool of still water, by an enlargement of the channel without a corresponding increase of the quantity of water to be discharged, or by entering the sea, the solid particles, which the water in a state of motion could carry along with it, will be deposited. So we find in most cases that a river, where it is narrow, is deep; where it is wide, its channel is encumbered with banks of sand or gravel, which have been deposited there by the slackening of the current. Upon entering the sea, the solid matter is naturally deposited, and thus a shoal comes to be formed just in front of the mouth of the river. In process of time this shoal increases, till at last it rises up to the water's surface, the stream being then divided into two branches. Each of these branches will become in course of time a channel similar to the main river, but of only half the size. The island formed between them will widen and lengthen, and become dry land; it may indeed be cultivated and inhabited. Meanwhile, however, each of the river branches may again have become subdivided, and new shoals, islands, or "deltas," as they are called, formed. Then perhaps on some occasion of a violent flood, when the stream has attained a great velocity and an overwhelming power, it will not wait to be di-

verted into its numerous channels, but bursts over the delta, and makes for itself a new straight channel out to sea. Then the original branches become more or less filled up as the current is diverted from them, and thus the spot which in the first instance was the river mouth is now many miles inland, or at the head of an archipelago of swampy alluvial islands. On a large scale this is the work of centuries, but it is always going on. The new channel forms another delta at its mouth; the same process is repeated; the river is divided and subdivided by the land it has itself formed. At the same time, the washing of the waves of the sea upon the light soil of which the new-made land is composed, continually tends to widen the channels, and the new deposits continually tend to make them shallow. Thus nature is continually at work to deteriorate the mouth of a river, and make it advance further into the sea.

These effects may be seen upon the map, which shows the mouth of every river discharging into a tideless sea to be situated on a part of the coast more or less projecting.

Now let us see how the mode of deposit from the water of a river is modified by the tide.

As far down as the point where the tide first becomes perceptible, the two rivers are in the same position; each brings its due quantity of earthy matter. In the case of the tidal river,

however, the river water does not fall abruptly into the still waters of the sea, but it mingles itself with the running tidal water, and the two flow on together to the sea. The proportion of tidal water is continually increasing, the channel widens and deepens, but the stream does not slacken, except for a short time at the change of the current. Thus, without any increase of the earthy matter, we have all the circumstances of a much larger river. We have the dimensions of the Nile, with the quantity of deposit due to the Thames.

It may be observed as apparently inconsistent with this remark, that the waters of a tidal estuary are much more muddy than those of the river itself. This is true, but the great bulk of the mud is never permanently deposited. It is washed up and down by the flood and ebb; the only actual accumulation is the quantity brought down by the river itself, and though it must be ultimately deposited somewhere, its quantity is very small, compared with the size of the great tidal estuary into which it is carried, and to the vast volume of water which is constantly flowing over it.

Again; the deposit will be distributed over the length of the estuary, according as the tides are more or less strong, or as the river water bears a larger or smaller proportion to the tidal water, so as to give more or less preponderance to the power of the ebb tide over the flood. Thus, while

in the case of a non-tidal mouth the deposit is confined to the point at which the river actually joins the sea, or to a comparatively short distance beyond it, to which the momentum of the water may carry the earthy particles; in a tidal estuary the deposit may take place in any part between the highest limits of the tide and the open sea. In the one case a year's deposit will be a bed of small extent, but considerable thickness; in the other a very thin layer over a large area. Suppose then that two rivers, similar in all respects, were to discharge themselves into funnel-shaped bays of the same form, but one in a tidal, the other in a non-tidal sea; how would the accumulation of ages affect each? In the non-tidal case, the accumulation would begin at the head of the bay where the current slackens; the form would become more and more blunted, but the lower end would remain unchanged till the deposit reach it in its regular course. In the tidal bay there would be a thin layer annually spread over the whole bay, or great part of it; some would be deposited at the head, but some would be carried to the mouth. From year to year the change would be imperceptible, but from age to age we should find the whole bay advancing a little seaward, but maintaining its form, or at least only changing it as inequalities were filled up, and the dimensions of

the gradually enlarging channel adjusted to the gradually increasing quantity of water which it has to pass.

On the other hand, if the two mouths were in the first instance of parallel width, instead of funnel-shaped, and if the soil were of a nature to be moved by water, the tide would immediately work away at the sides, and make for itself a funnel.

The form of a river mouth then depends upon the sea into which it falls being tidal or non-tidal. Where the sea is non-tidal, the river deposits form deltas, and the channels are divided and subdivided; where the sea is tidal, the material for the deltas is dispersed or spread over a larger space, while the tide forms and maintains for itself a channel, compared with the size of which the river deposits are insignificant.

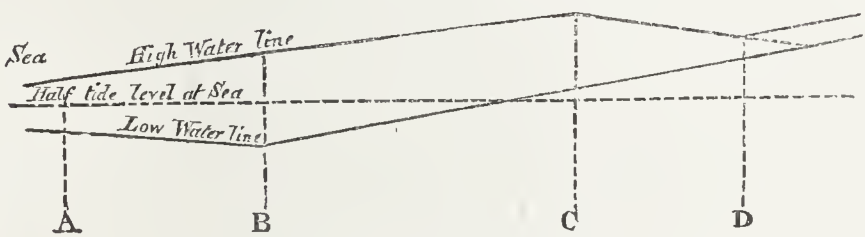
Having now seen how a river mouth is affected by the tide, let us see how the tide wave is affected on its entrance into the river.

The channel of a river is in fact a gulf which is very long in comparison with its width. The quantity of water required, therefore, to form the tide wave is considerable, and its entrance occasions a considerable current to set up the river during the flood tide.

Near the mouth the current does not change

with high water, but it follows the law of the sea tide, flowing up during the upper half of the tide, and down during the lower half. In proceeding up the river, however, the times of the change of current, and of high and low water approach nearer, and some miles up are generally very near together, though the stream generally continues a few minutes after high and low water, before it stops and changes its direction.

The manner in which the range of the tide varies, as the wave passes up a river, will be best understood from the accompanying diagram.



The mouth of the river is at A, where the range of tide is that of the neighbouring sea. After entering the river, the wave increases, both by high water being raised, and low water being depressed, according to the ordinary law of a gulf wave, the mean or half tide level remaining nearly the same. This increase of range is well marked in some very long river mouths. At King Road, for instance, in the Bristol Channel, the level of low water is 12 to 14 feet below that of low water

at sea, and the high water is as much above high water at sea. In the Mersey, low water a little below Ellesmere Port is some inches lower than at sea. This increase of range continues so long as the channel is sufficiently wide and deep to allow the full undulation of the wave. An estuary of considerable length and depth is required for this division of the tide to be manifested. In a small estuary, the length (A B in the diagram) will be much reduced, and perhaps A and B may come close together, so that no depression of the low water will be found.

Above the point B the character of the tide changes. Its channel can no longer be considered a branch of the ocean, but is a river of running water, with a surface and bed naturally sloping towards the sea, and a current more or less strong, opposing that of the tide. At first, however, the channel at high water is large, and the wave has room to develop itself to its natural size, which should be greater than at B, so the high water is higher up to a certain point, C; although at low water the channel has become too small to allow of a free undulation, so that the lower half of the wave diminishes, while the upper half increases, the high water line then inclines upwards, but the low water line still more so, and the range of the tide decreases.

Beyond C, the resistance to the passage of the wave has so increased that it cannot maintain its height even at high water, and the high water line begins gradually to incline downwards, so that the range of tide decreases more rapidly than before, and at a certain point (D) it will meet the low water line and the tide will vanish.

In some rivers, however, there is still a fourth phase of the tide. If the river channel above D be pretty large, a small wave will be propagated along it, and it may even mount many feet above the level of the sea. Thus, in the Ganges there is a sensible tide at a distance of 240 miles from the mouth, and at an elevation of 80 feet above the level of the sea. In the Amazon it is felt at a distance of 600 miles, and at an elevation of 90 feet. In our small rivers the channels are generally too small for the propagation of a wave upon the land water, and there is seldom an elevation greater than that due to the increased range of the sea wave, but there are cases in which it appears to some extent. In the Tay it is stated that there is a tide, even where the low water of the river is higher than the high water of the sea. In the Severn, at Worcester, there is more rise of tide when the river is raised some feet by land floods, than when it is low. When the floods rise still higher the tide again dis-

appears[1]. When the river is low, the channel is not sufficiently free for the propagation of the wave. When flooded the height is too great.

The points B, C, and D are by no means invariable. B cannot change much, but C will be higher up the river as the tide is higher, and D varies not only with the height of the tide, but also with that of the land water. A higher tide sends it obviously higher up the river, and a fuller river, as we have just seen, may either assist or impede its advance.

These general principles will give an idea of how the flow of the tide in a river is within the control of art. If the low water channel between B and C be deepened and widened, the point B, where there is the greatest depression of low water, will be brought higher up the river, and facility given for the point C, the summit of the high water line, to reach higher up. This of itself will push on the point D; while a farther enlargement between C and D will again facilitate the progress of the wave in this division, and by making the high water line in C D more level, throw the point at which it meets the low water line, or where the tide ceases, to a greater distance.

[1] The tides are by recent works, for the benefit of navigation, shut out at Tewkesbury, 12 miles below Worcester.

In this manner more tide comes into the river, and not only itself assists the navigation of the river, but increases the quantity of water that will flow out and maintain the size of the channels near the mouth.

Another peculiar effect of the river channels upon the tide must be noticed. Bearing in mind that the rate at which the wave travels is dependent upon the depth, and that the depth near low water, or when the wave first enters, is much less than at high water, it will be obvious that the foot of the wave will travel much more slowly than the summit, and that at a certain distance from the mouth the period of flood, i. e. from low water to high water, while the tide is rising, will be much less than the period of ebb, while the water is falling. The tide may take only $4\frac{1}{2}$ hours to rise and 8 hours to fall. Now the effect of this is important. In such a case there is as much tidal water to run up the river in $4\frac{1}{2}$ hours as there is to run down in 8 hours; and therefore, so far as the tidal water is concerned, the flood current, so long as it lasts, must be stronger than the ebb. There is, however, to set against this the land water current, which increases the ebb and diminishes the flood, and so to a certain extent neutralizes the inequality. It does not, however, make a perfect balance. In most rivers, especially in the summer and autumn, when the

quantity of land water is small, the flood tide is in certain parts stronger than the ebb, and the effect is, that it bears with it certain earthy matters which the ebb tide is not strong enough to carry back, and which are not removed till the floods of winter arrive.

Here is another particular in which art may usefully direct and modify the operations of nature. The larger, deeper, and freer the low water channel, the less will the foot of the wave be retarded in comparison with the head, the longer will the flood tide continue, the less will be the velocity of the current, and the more will the powers of the ebb and flood be equalized.

This inequality in the periods of flood and ebb is increased as we go higher up the river by another cause, viz. the inclination of the bed, which prevents the rise from commencing at all till the tide at the river mouth has mounted considerably. Thus in regions to which only the top of the wave can reach, flood tide may not last more than an hour; true ebb tide will not last much longer; but the transition from ebb tide to the ordinary river flow will not be detected. Even here, however, there is the same retardation of the flood tide when it first enters the river channel.

In cases where the tide is very large and the channel very shallow, this retardation of the flood tide is productive of a curious phenomenon, called

"the bore." The bore is caused when the tidal current necessary for the supply of water is more rapid than the transmission of the foot of the wave. It therefore cannot wait until the channel is tranquilly enlarged by the raising of a wave in it, but the water rises in a foaming head like a great breaker on the sea-shore.

The most remarkable instance of a bore in this country is in the Severn, about 20 miles below Gloucester.

The high water channel is here nearly a mile wide, but the low water stream is not more than a quarter of that width and from 2 to 3 feet deep; the remaining space is occupied by flat sand banks. The first approach of the tide is indicated by a distant roaring sound, and presently 2 or 3 miles off may be seen a low white line stretching across the river bed. This comes nearer and nearer, till in a few minutes it becomes distinctly visible and audible as a breaking wave 2 or 3, and sometimes 5 or 6 feet high. Where the bottom is shallow it rises higher and moves more slowly; where the water is deeper it moves more rapidly, decreases in height, loses its foaming surface, and becomes simply a gentle swell. Behind the bore follows an impetuous torrent of muddy water, rushing up the river; an instantaneous rise of 3 feet has been effected, and the rise continues rapidly increasing. In 25

minutes from the approach of the bore, the space which had been dry sand is covered with a crowd of vessels, some of 150 tons burden, sailing safely over it, carried along by the current at the rate of 7 or 8 miles an hour. A single sail is set, or a boat with two rowers is towing each vessel, to give her a little motion through the water and the power of steering, but the moving force is the tidal current. In a few minutes 40 or 50 vessels will have passed; they must not be later, or they would "lose their tide;" the current would fail them before they could get into a place safe from the bore of the succeeding tide, which if it caught them in the open river would roll them over and bury them in sand. The tide, however, continues to rise, and in an hour and three-quarters from the passing of the bore it has risen 18 to 20 feet. From this point the river makes a bend in the form of a horse-shoe, and returns after a course of 8 miles to a spot $1\frac{1}{2}$ miles distant from the point at which we have supposed the tide to be first watched. If after the passage of the ships the spectator were to walk over this mile and half, he would find the river again tranquilly flowing towards the sea. Presently the roaring of the bore will be heard, the banks will be covered, the fleet of coasters will pass on their way (if it be a good tide some of them will "carry it" to Gloucester), in an hour the water will have risen 10

feet and the current will turn. Let the spectator now return to his starting-point (Hock Crib), and he will find the river much in the same tranquil state as when he first saw it. The tail of the tide wave alone remains, and the Severn is within the space of 4 hours once more a waste of sand and mud banks.

There is a bore in some other rivers, the Great Ouse, the Parrot, and sometimes the Dee, at Chester. In the Hoogly, the Calcutta mouth of the Ganges, it is very strong, and may be heard for many miles. It is also strong in the Amazon. The cause is the same in all, the resistance of the low water channel to the passage of the wave. It is an extreme case of the retardation of the flood tide, and may be avoided by an enlargement of the low water channel, so as to admit the wave more freely.

CHAPTER XII.

IMPROVEMENT OF TIDAL RIVERS.

The Thames. The Clyde. The Ouse. The Nene, and others.

WITHIN the last hundred years many very important works have been accomplished for the improvement of tidal rivers, based always upon the principle of facilitating the admission of the tide wave. It may not be uninteresting to notice some of these.

The Thames is probably the most instructive example of all. The artificial works executed upon this river in modern times have been the deepening of the bed below the city, and the removal of old London Bridge.

The effect of the deepening has been that, whereas in 1720 the flood tide commenced only 3 hours 50 minutes before high water, in 1849 the passage of the early flood had been so facilitated, that the water at London Bridge began to rise 5 hours 15 minutes before high water. The time of high water itself has also been accelerated.

It now takes place about 2 hours after the moon's transit. In 1683, it was generally reckoned 3 hours after the transit, but in 1213, according to an old time table which is still in existence, the time of high water is given as 3 hours 48 minutes, when the moon was one day old, which would be rather more than 3 hours after the transit, so that in the 470 years previous to 1683 there appears to have been little alteration, while in the 170 years following, the high water was accelerated an hour, and the low water at least two hours and a half. Within the last 20 years the change has been still more rapid. In 1833, high water at London Bridge was 1 hour 37 minutes after Sheerness; in 1851, it was only 1 hour 20 minutes, being a gain of 17 minutes in 18 years. It was during this period that the great changes in the river bed, caused by the removal of old London Bridge in 1833, took place.

Old London Bridge was more like a huge dam with 19 sluices in it than a bridge, according to our modern notions. At low water it dammed up the river, so that the water surface was 4 to 5 feet higher above bridge than below, and at high water it was 8 inches to a foot higher below than above. The obstruction caused by the new bridge is scarcely perceptible either to the flood or ebb tide.

Now let us see the consequences of this change:—

First, the low water level of the Thames has been lowered all the way from London Bridge to Teddington Lock, 4 feet at the former place and about 2 feet at the latter.

Secondly, this drawing off the water, as it were, had the effect of materially increasing the rapidity of the current, for the water delivered over the weir at Teddington, which had not altered in quantity, had now to find its way to London Bridge through a smaller channel than formerly. This increased current wore away the bottom, and so lowered the bed of the river; but not to the same extent that the water surface had been lowered. Thus on the whole, between London Bridge and Teddington, the channel is worse than it was.

Thirdly, on account of this deterioration of the channel, the tide gets less easily to Teddington than it did formerly. It therefore does not rise so high by 6 inches to a foot as it did, and the foot of the wave being more retarded than the head, the duration of flood tide has decreased by from 13 to 20 minutes. So far, therefore, the removal of old London Bridge has had an injurious effect upon the flow of the tide; but,

Fourthly, on account of the lowering of the

low water between London Bridge and Teddington, the tide has so much more space to rise and fall in, and though it is not quite so high at Teddington as formerly, yet it is higher just above bridge, owing to the obstruction at high water being removed. Thus on the whole the high water line remains the same, and the entire space gained by the lowering of low water is given to the range of tide. This has increased the total quantity of tidal water flowing in and out twice a day, by probably, on an average of all tides, not less than a fourth part; and this has been added to the available water flowing in the Thames below bridge, and past the dock entrances, where it is so valuable to navigation. To this grand increase of tidal water we must attribute in part the progressive improvement of the port of London. The increased depth has been dredged by machinery, but the places dredged would have been more or less filled up again by deposits of sand and mud, if there had not been provided an increase of water corresponding to the increase of the channel.

Nature does not often work suddenly. The channel between London Bridge and Teddington is gradually improving itself, and if it were assisted by art, in deepening the bottom, and making the sides more uniform, and so not only lowering the river altogether, so as to admit more tide, but, by

giving it more play, enabling it to rise higher, the improvement would still go on. Already nature has done much, as the failure of the foundations of Westminster and Blackfriars Bridges testify, but some help is required to give her good intentions their full effect.

One of the most remarkable monuments of engineering science and skill on record is presented in the river Clyde and port of Glasgow; and although the case is one which presents less variety in the action of the channel on the tide, and the reaction of the tide on the channel, than the Thames, yet the same laws hold good in each case, and the reader will understand from the one how nature has supported and assisted art in the other.

In the year 1755, the citizens of Glasgow, desirous of extending their trade, applied to the celebrated John Smeaton, the builder of the Eddystone Lighthouse, and the leading engineer of the last century, for his advice as to the best mode of making their river navigable. He reported that he found at low water, in many places below Glasgow, a depth of not more than 18 inches, and at high water 3 to 4 feet; a depth evidently insufficient to float any useful class of vessels. He proposed, as a remedy, the construction of a dam or weir and a lock at Marlinford, 5 miles below Glasgow, which should pen back the land water, so as to give a constant depth for a boat, after

passing the lock, of 4 feet 6 inches. Of course this dam would have entirely excluded the tide from Glasgow.

Fortunately this recommendation, though coming from so high an authority, was not followed, but thirteen years later, in 1768, a Mr. Golborne, also a celebrated engineer, was consulted. He advised making jetties of stone across a portion of the river in those parts where it was wide, so as to confine the width of the channel, and at the same time to cut through the shoals, so as to increase its depth.

This plan was approved and commenced, and such was the success, that in a few years there was a depth of 6 feet at all times of tide up to Glasgow, already 18 inches more than Smeaton had proposed.

Mr. Rennie, in 1799, advised the still further removal of obstructions, and finding that the cross jetties caused eddies and inequalities in the current, he recommended joining their ends by stone walls, so as to make new continuous banks to the river.

Mr. Telford, in 1806, advised perseverance in the same principle, and that in farther improvements the cross jetties should not be made at all, but continuous walls on each side the river substituted. About this time steam power was first employed to dredge the bottom, and much facilitated the operations.

A vessel drawing 8 feet 6 inches could now come up to Glasgow with an ordinary spring tide. Already nearly double Smeaton's proposed depth had been obtained.

This system of confining the current by side walls, and gradually deepening the low water channel was continued under the advice of Rennie and Telford till 1821, when Mr. Rennie died. Previous to his death he had the satisfaction of seeing that a vessel drawing 11 feet could reach Glasgow more easily than one drawing 8½ feet could, when he was first consulted. The same principle was continued under Telford alone; the river walls were lengthened, and the river brought to that regular taper form which we have seen to be so conducive to a good flow of tide.

Since Mr. Telford's death, in 1835, Mr. Walker has directed the operations. Up to 1850, according to Sir John Rennie, 1,278,000*l.* had been expended upon the river and harbour of Glasgow in gradual improvements; a large sum, but let us see the results in the profits accruing.

The tonnage dues from which the revenue is derived amounted in

1771,	to	1,071*l.*
1791,	„	2,145*l.*
1825,	„	8,408*l.*
1847,	„	31,900*l.*

and they are now approaching, if they have not surpassed, 70,000*l.* per annum.

Let us compare the state of the river in 1755 and 1850:—

	1755.	1850.
Depth at high water .	4 ft. 6 in.	16 to 17 ft.
Rise of tide . . .	very small.	9 ft.
Duration of flood current,	barely perceptible.	$4\frac{1}{2}$ hrs.

The time of high water has been accelerated 20 minutes, and it flows now a foot higher than it did in 1824. Probably at that time it flowed higher than in 1755. It is expected that farther improvements will make it flow still earlier and higher.

This work then is yet unfinished. In making a tide to flow 9 feet twice a day, man has brought to his aid an agent, to whose power it would be presumptuous to fix a limit; and another 20 years may witness changes in the port of Glasgow as great as the past 20 have shown.

Four principal rivers discharge themselves into the Wash, between Lincolnshire, Cambridgeshire, and Norfolk, the Ouse, the Nene, the Welland, and the Witham. On these rivers are situated respectively the ports of Lynn, Wisbeach, Spalding, and Boston; and each has been the scene of considerable operations.

The country lying around the whole of these rivers is very low; often below the level of high

water, and in many parts only capable of drainage by means of wind or steam to pump up the water from the drains into the rivers. The works of improvement have therefore been directed as much to the interests of drainage as of navigation, by lowering the level of low water, and thus allowing the land drains at once to fall into the river channels without the necessity of pumping. Both navigation and drainage, however, have equally benefited.

The Ouse, above the town of Lynn, formerly took a very circuitous course. In 1818, a new straight channel, called the Eau Brink Cut, 2½ miles long, was commenced, to intercept a circuit of 5 miles, and when the river was turned into it in 1820, the effect was to lower the low water 5 feet at the head of the cut, giving this additional fall for the outlets of the land drains, and this additional space for the admission of tidal water. The inhabitants of Lynn feared that this lowering of the water, and increase of the power of the tidal current would have undermined their wharves situated on the banks of the river, near the lower end of the cut, and such no doubt would have been the effect, if the river had not taken another and more direct course out to sea, leaving only an accumulation of mud and sand in front of the quays. The river channel, however, has been re-directed upon the wharves, and

by that means an additional depth of 4 feet has been given without causing an incontrollable scour.

Meanwhile the old channel of the river became also filled up, and was converted into pasture land. The cut itself has been considerably deepened by the force of the current since it was opened, and the channel being thus more and more enlarged, the tide mounts higher, as well as falls lower.

The principal effect of this cut, the lowering of the river above, by the substitution of a short for a long channel to the sea, would have been attained if there had been no tide; but the flow and ebb of the tide materially assist the effect, by increasing the current, the power which maintains the channel; and also, probably, *now* in some measure, and certainly if the same principle were carried farther, by communicating the tidal undulation to the river water, and so making it ebb out below its natural level, like the water at the head of the Bristol Channel, and at Gravesend. This lowering of the bed of the Ouse has been the foundation of a vast system of drainage lately applied to a large district of the neighbouring fen country, which has almost entirely avoided the necessity of pumping the drainage water, by giving it a natural outfall, and has immensely increased the value and resources of the land. The Ouse is

now being still farther improved below the town of Lynn by another new straight cut, made by the Norfolk Estuary Company.

The operations in the Nene were carried out on the same principles as in the Ouse, a straight cut $5\frac{1}{2}$ miles long called the Nene outfall being substituted for the old winding course of the river below Wisbeach. The water at the head of the cut was thereby lowered $10\frac{1}{2}$ feet, and a vessel drawing 14 feet of water can now get to Wisbeach more easily than one drawing 6 feet could formerly. In this case also the operations are being continued, and far more important results may be anticipated.

The same principles were followed on the Welland and the Witham. In the latter case there is now a depth of water of 14 feet where formerly there was only 3 or 4 feet, and a greater increase is only prevented by the existence of a dam across the river at Boston, which prevents the flow of tide above the town.

The flatness of this fen country, and the light material of the soil, render river works very inexpensive. A new channel quickly enlarges itself when the water is directed through it. If all the rivers were opened out to the entrance of the tide, instead of being dammed up for the benefit of inland navigation, as they are at present, the effects of the ebb and flow would be most im-

portant. Much has already been done, and much more yet remains.

We might mention other cases of the artificial improvements of rivers by a judicious direction of the operations of nature. In the Dee below Chester 120 years ago a new channel was made, 10 miles in length, which enabled vessels to come up to the town, instead of discharging their cargoes into lighters at a distance. In the Ribble, the Lune, the Tay, the Forth, the Tyne, the Wear, and many other rivers, the same principles of deepening the channels so as to admit more tide have been carried out, and in all cases with success. The flux and reflux is the great natural agent in the maintenance, and to some extent also in the formation of the navigable channels.

Like all other true principles, however, this doctrine of the importance of tidal water may be carried to an extreme, and of late years it has given rise to much discussion in particular cases. By misapplication of a true principle, mischief has often been done. Even in the Clyde, where success has been so marked, persons have not been wanting who have begrudged the space cut off in contracting the channel, a necessary accompaniment to its deepening. The fact is, that while we admit that every cubic foot of water which flows in and out of a river is of value, that value may be greater or less according as it is

well or ill directed, and cases may arise, and often have arisen, in which a less quantity well controlled is of more value than a greater quantity uncontrolled. This is not the place for a discussion of vexed questions, but having expressed our conviction of the great importance of the tidal flow to the interests of navigation, we must protest against the indiscriminating universality which we think has sometimes of late years been given to the principle.

CHAPTER XIII.

RANGE OF TIDE AND LEVEL OF THE OCEAN.

Causes of increased range of tide. Dimensions of the tide wave differently affected at different heights. River tide part of a wave. Low water sometimes lower at neaps than at springs. Mean tide level invariable. Effect of winds, and weight of the atmosphere. Land floods. Recapitulation. Conclusion.

In following the sketch which we have given, the reader cannot fail to have been struck with the great varieties in the dimensions of the tide wave. We have already explained that the conformation of the shores and bottom will cause some variation, but there are certainly other laws guiding the range of the tide, of which we are as yet ignorant.

It has been found by experiment, as we have before stated, that a wave, in travelling along a channel which gradually contracts in width, becomes higher and higher, and that in emerging from a contracted to a wider channel, it diminishes in height. Observation with regard to the tide wave proves that it also is subject to both these

laws. In the mouth of almost every river the tide is greater than on the shore of the neighbouring sea. Of the converse law an obvious instance occurs in the Mediterranean, where the tide which was 9 feet high at the Strait of Gibraltar is almost entirely lost.

The meeting of two distinct waves may cause either a combined wave of double height if their summits coincide, or an obliteration of both, if the summit of one coincide with the hollow of the other.

These two causes, however, converging channels and combining waves, are not sufficient to account for many of the great ranges of tide which we find. For instance, the tides of the north-west coast of Australia, and of the eastern coast of Patagonia. Each is the scene of the meeting of two tides, but in neither case would the two meeting tides simply mounted one upon the other cause so great a range. In neither case is there any apparent conformation of the land sufficient to account for the increase, but there is evidence of the wave being stationary rather than progressive in one case, and of a very peculiar movement in the other. There is probably some law of undulation not yet clearly understood on which depend these and similar cases.

The great rise in the Bristol Channel we might attribute to the bell-mouthed form, but we have

a nearly equal rise, and a proportionately greater increase from the mouth to the head, in the Bay of St. Malo, which has a very imperfectly formed bell mouth; while in the numerous estuaries around our coasts of a form very similar to that of the Bristol Channel, we find a very obvious increase of range in every case, but generally to a much less extent. Thus the Thames tide increases from 13 feet at the North Foreland to 22 feet at Gravesend; that of the Humber from 19 feet at Grimsby to 21 feet at Hull; that of the Frith of Forth from 14 feet at Fife Ness to 16 feet at Leith; of the Murray Frith from 10 feet at Wick and Banff to 14 feet at Dornoch and Nairn; and in the Shannon the tide gradually increases from 13 feet to 18½ feet. In none of these cases is the increase of range so great as in the Bristol Channel, and the Bay of St. Malo tides are a still stronger case. We may mention, however, two cases of gulf tides which are still more extraordinary, and seem to deserve especial investigation, viz. the Bay of Fundy, where the tides increase in range from 13 to 60 feet; and the Adriatic Sea, where they increase from something too small for ordinary observation to from 3 to 5 feet at Venice. In both these cases, however, the information we have been able to find is very meagre. The Gulf of California is remarkable in form, and we might presume would ma-

terially affect the tide. It appears, however, that at Guaymas Harbour[1] half way up the gulf, the rise is only 4 feet, even less than in the open sea at the entrance. Professor Airy states that there is a considerable increase at the head of the gulf[2], but does not give his authority. It is not improbable, if this be true, that there is a node near Guaymas. We have remarked upon the evidence of a somewhat similar movement in the Red Sea. On the whole, we may admit that the causes of the most remarkably high tides and increasing ranges is a question yet open to philosophers.

The causes, whatever they may be, which increase the dimensions of a tide wave, sometimes act unequally at different states of the tide. Thus at Plymouth, Dr. Whewell found in investigating the levels of low water, as they varied from day to day, with the varying positions of the heavenly bodies, that low water was more affected than high water; that a change of the moon's declination, for instance, which would raise the high water at Plymouth 6 inches, would lower the low water 9 inches, and the same holds good for all other causes of variation. From this it would appear that the influx of tidal water to Plymouth Sound changes its nature as a tide-augmenting channel.

[1] Admiralty Chart.

[2] Encyclopædia Metropolitana. Article, "Tides and Waves."

In a river, although, as we have before explained, the actual range of tide decreases above a certain point, yet the proportions of the tide may, and in some cases do increase. The rise is due, not to a *smaller wave*, but to a *part of a greater one.* The difference is important, because although the difference of level of high water and low water is small, the difference between the high water of a great tide and the high water of a small tide is considerable. Thus at Hock Crib, on the Severn, for instance, where the tide rises 18 feet, it is not a tide wave 18 feet high, but the upper part of a wave from 40 to 50 feet high. The rise and fall are proportionably rapid, and the river remains for several hours in the day without tide at all. At this point neap tides only rise 5 feet, and a few miles higher up they are not felt at all, so that tides only come for a few days at the springs.

This produces a curious anomaly. Where there is a complete tide wave, low water of spring tides is lower than low water of neaps; but in a river where only a part of the wave enters, and neaps are little felt, the low water may be lower at neap tides than at springs, owing to the river channel not having time to pass off the great quantity of tidal water which has been thrown in, before the next tide comes. The more perfect the channel, however, the less will this be the case, and in a good state of the river it is probable that, even

though the whole wave may not have access, yet the spring tide, by its greater undulatory force, would draw off the water more than the neap.

A very curious case is found at Ballytaigue Lough, in the county of Wexford. This lough, though of considerable extent, has a very narrow communication with the sea. The effect is, that while *outside* the entrance, spring tides rise 11 feet, and neaps 6 feet; *inside*, springs rise only 2 feet, and neaps 3 feet; the low water of spring tides being nearly at the same level as high water at neaps. The quantity of tidal water is limited, not as in an ordinary case by the extent of the lough, but by the capacity of the entrance to pass it. During springs, more runs in than can run out, and the water in the lough is high; during neaps, more runs out than can run in, and the water in the lough is low.

All the observations that have been made on the subject tend to show, that whatever may be the different ranges of tide at different places, the mean tide level, that is, the point half way between high and low water, is the same at all places on the sea-coast, not in rivers; that in fact the tide is an oscillation of the water to an equal height above and below a fixed level. It was found by experiment, that the level of half tide in the Bristol Channel, where the range is from 40 to 50 feet, is the same as on the south

coast of Devon, where the range is 13 feet, and a very extended series of observations, made under direction of Professor Airy, on the coast of Ireland, prove that there, notwithstanding the great varieties in the range of tide, mean tide level is the same every where, and at all times. If there be any variation, it is that in summer the mean tide level is a little lower than in winter.

This mean tide level, however, is liable to be changed by meteorological causes, by winds, and the weight of the atmosphere. These causes are often spoken of as affecting *the tide.* This, however, is incorrect, at least in the main; what they affect is the level of *the sea,* high water and low water equally; the *tide* remains the same.

Generally speaking, the wind heaps up the water upon the shore against which it is blowing, and it heaps it up the more, according as the width of water over which it has been blowing is greater. South and south-west winds, which blow over the great expanse of the Atlantic, have with us the greatest effect in raising the level of the sea, and if the direction change at a critical moment from this to a direction which blows upon any particular point of the coast, the greatest effects are produced.

The effect of the weight of the atmosphere appears to be pretty regular, but it is difficult to separate it from that of the winds, which is more

complicated, especially as the most violent winds generally accompany a very light atmosphere and low barometer. Experiments have been made at London and Liverpool as to the coincidence of the variations of level of the barometer and the sea. From them it appears, that a fall of 1 inch of the barometer is accompanied by a rise at Liverpool of 11 inches of the water, and at London of 7 inches. The difference is probably owing to the greater distance of London from the open sea, and the consequently greater difficulty in the escape of the water under pressure. Sir J. C. Ross in 1848 made a series of experiments in the Arctic regions under circumstances very favourable to the determination of this question, being in a locality where the tide was little affected either by the agitation of the sea or by local winds, and he found that a rise of 1 inch of the barometer was accompanied by a depression of the sea of $13\frac{1}{2}$ inches. Now it is curious that if a barometer were made with sea water instead of mercury, it would rise and fall about $13\frac{1}{2}$ inches for every inch of the mercurial barometer, from which it would seem that the open sea is a great natural barometer, indicating the weight of the air. The sea and the atmosphere, both fluids, so arrange themselves as to equalize the total pressure upon the earth, when one is lighter the other is heavier.

Many of our ports being situated upon rivers, a third cause of disturbance of mean tide level becomes important, namely, freshes or land floods. These are generally imperceptible at the mouth of a river, but higher up they sometimes raise the surface of the water as much as 20 feet. Under favourable circumstances, and to a certain extent, as we have seen in the case of the Severn, they assist the tidal flow, but in greater force they overpower it. In all cases in a river they raise the level of both high and low water, but the latter more than the former, so that the range of tide is diminished. They are a very valuable agent in scouring out the bed of a navigable river where the tide does not reach in great force. In fact, the navigation of a tidal river may be said to depend upon these two agents, the land floods great above, and gradually diminishing in descending; and the tides great below, and gradually diminishing in ascending.

We have now concluded, though in a very imperfect manner, the task which we proposed to ourselves.

I. We have shown that the attractions of the sun and moon must cause a periodical disturbance of the waters of the globe, in some respects similar to the tides we see.

II. We have seen that this periodical disturbance is so slight, that in its primary form it is

difficult to detect, and it is doubtful if it is any where evident.

III. We have, however, by the assistance of our knowledge of the laws of waves, found that this disturbance, though so slight in its primary form, is capable of transmission from one part of the ocean to another, not only without diminution, but in certain circumstances with great increase of its effects; so that in its secondary form it may become a very important natural agent.

IV. We found the nearest approximation to the primary wave in the Pacific Ocean, and traced its transmission, in its secondary form, into the Indian and Atlantic Oceans.

V. We traced a single branch of this great oceanic undulation into our own inland seas, where it assumes the form of a stationary wave rising and falling without progressive motion. This is an example of one of the many forms which the undulatory movement may take under the influence of confinement, diversion, and combination.

VI. We traced the tide wave into rivers, the localities in which it is of the greatest importance to mankind, and we have shown how far it is under the control of human operations.

In conclusion we may repeat, that while we cannot but recognize the primary cause of the tides as having been determined and investigated

with mathematical precision, yet that the secondary influences, by means of which alone we are enabled to compare the astronomical laws with observation, are involved in very great mystery. We know just enough to show us that we are in the right road, but that we must tread in it carefully, or we may easily be led astray. The general direction is fixed, but the particular course of a great main wave, or the particular movement of a local undulation, we must judge of diffidently, leaving a wide margin for the modifications which newly discovered facts may make in our ideas.

THE END.

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